STRUCTURE AND GENESIS
of
THE IRON ORES OF BICHOLIM, GOA.

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Chapter I

INTRODUCTION

GENERAL STATEMENT

The mining and extraction of iron has been practised in India from the time immemorial. India's assessment of total iron ore reserves is about 210,000 million tons i.e., about 25 °/o of the total world reserves. But so far as her output is concerned she is the sixth iron ore-producing country of the world.

Some of the well-known Indian iron ore deposits and workings are located in the states of Bihar, Orissa, Madhya Pradesh, Mysore and Goa. These deposits have been drawing special attention of the Indian as well as many of the world's consumers and natural resources investigators since independence.

Iron ore deposits in the present Indian Union territory of Goa are also known for a very long time. But they were of little interest to India till the territory was freed from the Portuguese in 1961.

The earlier Portuguese government did not take any interest to carry out systematic geological surveying and mineral prospecting in Goa so long as it remained under their occupation. As a result, neither any previous geological map nor any official useful information regarding the geology and mineral resources of the territory was available. About a year after the liberation

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This is to certify that Mr. A.K. Majumdar has completed his research under my supervision for the degree of Doctor of Philosophy of the Aligarh Muslim University. This work is an original contribution to the existing knowledge of the subject. It contains some important new observations as well.

He is allowed to submit the work for the Ph.D. degree of the Aligarh Muslim University, Aligarh.

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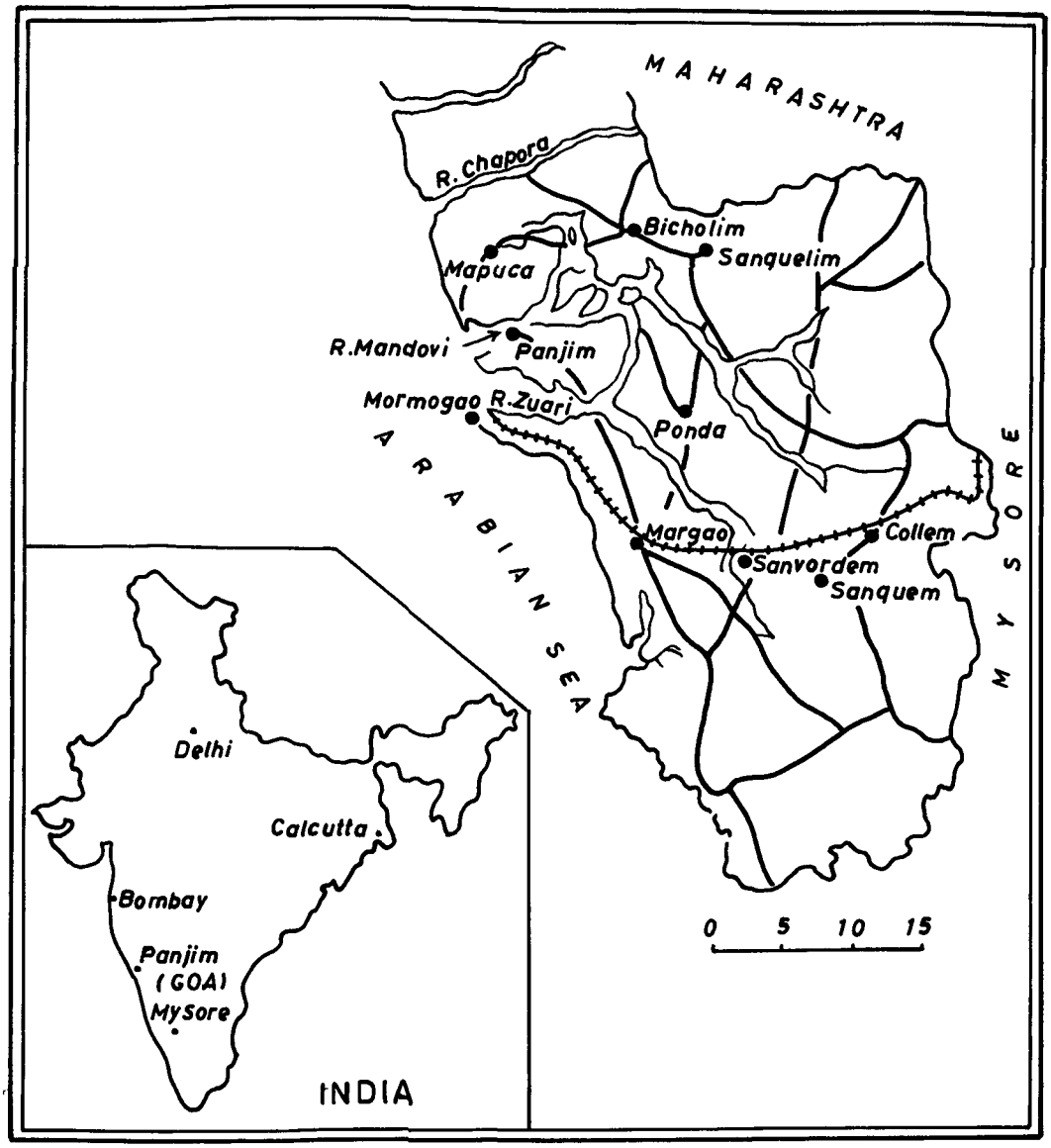

FIG. 1 LOCATION MAP

of Goa, both the Geological Survey of India and Indian Bureau of Mines extended their activities in the territory in order to survey and assess for the first time its mineral resources. As soon as the administration became normal after the liberation movement, the present worker availed of the first opportunity to enter Goa with the purpose of investigating one of its largest and important deposits of iron ore.

The present work includes the study of geology, structure, mineralogy and genesis of the two well-known iron ore deposits viz., Bicholim ($15^{\circ}35'15''$; $73^{\circ}57'$) and Sanquelim ($15^{\circ}34'$: $74^{\circ}30''$) of Bicholim taluka (= subdivision) , Goa. It is hoped that this study might be useful to compare the iron formations of Goa with similar other formations occurring elsewhere in the country. It may even be of great help to the future workers particularly, those who may wish to work on the structure, mineralogy and genesis of similar other Precambrian iron ore deposits of Goa and also of the adjacent state of Mysore.

LOCATION AND ACCESSIBILITY

Goa is situated on the west coast of India, about 350 Km south of Bombay, between latitudes $14^{\circ}53'$: $15^{\circ}48'$ north and longitudes $73^{\circ}45'$: $74^{\circ}24'$ east. It has an area of about 3,600 sq.km. The territory is partly bounded by the states of Maharashtra on its north and northeast and Mysore on its south and southeast, the Arabian sea demarcates its entire western boundary (Fig.1).

In north Goa there is a small town at Bicholim where the present head quarter of Bicholim taluka is located. The town is about 35 Km northeast of Panjim, the capital of Goa. In the Londa-Vasco-de-Gama section of Southern Railway, Colem Sanvordem and Margao are the railway heads of Bicholim. The other possible approach to the area is by sea from Bombay to Panjim and then the remaining distance by road.

TOPOGRAPHY AND DRAINAGE

Physiographically, Goa can be divided into three well-defined regions viz., 1) the hilly coastal belt with a few sandy stretches facing the Arabian sea, 2) the hilly sub-Ghat, which occupies a greater part of the country and 3) the mountaneous region of Western Ghats along its northern and eastern boundaries. The area under consideration falls within the sub-Ghat region. It has a varied topography consisting mainly of highlands and low hills. The hills are generally woody and rugged, more or less flat-topped and scattered. In contrast to these low hills there are a few well-defined hilly tracts of which Sirigao (161.54 m) is the one whose northern side rises abruptly from the plains while its southern side gradually slopes into small, flat-topped and isolated hills (Fig.2). The Sanquelim hill (97.03 m) also shows similar topographic features with the exception that its southern slope abruptly merges into a wide plane which extends upto the main drainage basin of the area beyond Virdi ($15^{o}33'$: $73^{o}54'30''$). Other significant higher

topographic features in the vicinity are Mulgao (136.70 m), Dudonem (147.68 m), Sanquelim (135.42 m), Maulinguem (131.57 m), Porlem (121.68 m). Rest of the area is low-lying. The relief of the area is approximately 130 meters.

The drainage network in northern Goa is considerably dense (Fig.2) due to the fact that it lies on the windward side of the Western Ghat escrapment and hence a suitable site for heavy monsoonic precipitation. In the greater part of the area, however, there are two distinct directions of drainage, some flow more or less at right angles to NW-SE, the general strike of the hill ranges and others, more or less parallel to them. The third order meandering streams of the area viz., Bicholim, Valvota and Arvalem are sluggish and flow more or less across the ranges. All these three streams join together on the southern boundary of the area, near Mati ($15^{\circ}33'$: $73^{\circ}58'30''$) and flow southwards for about a distance of one Kilometer before joining the main river, Madei. The smaller streams and nalas (= brooklet) are mostly seasonal and more or less follow the regional strike of the hill ranges. Accordingly, the stream courses have developed a trellis pattern in the topographically uneven portions of the area. In the flat-lying coastal belt the dominant stream pattern is dendritic.

CLIMATE AND RAINFALL

Goa enjoyes a tropical climate with an average temperature of $27^{\circ}C$ and an annual rainfall of about 3,500 mm. About 60 $^{\circ}/o$

of the precipitation is received from June to August. The climate is very much influenced by the moisture-laden wind. The monsoon breaks in early June and withdraws by early October. During this period humidity varies from 90 °/o to 95 °/o. In rest of the year humidity varies from 80 °/o to 95 °/o. The summer season lasts from March to May when murcury column touches nearly 32°C. The period between December to February is rather cool and dry.

AREAL EXTENT AND ROCK EXPOSURE

Most of the important workable iron ore deposits of Goa occur in the northern part of the river Madei (Fig.2). These deposits constitute the iron ranges of Sirigao-Sanquelim, the Onda-Valguem-Pale and the Onda-Pissurlem-Vantem. The present study is confined to the iron ore deposit of Sirigao-Sanquelim range.

The investigated area extends lengthwise from Sanquelim on the southeast to Sirigao (15°36'15" : 73°54') on the northwest. Its northern and southern boundaries are roughly demarcated by the localities, Nanora (15°38' : 73°55'30"), Curchirem(15°36' : 74°0') and north of Poriem (15°35'15" : 74°1'30") on one side and Dudonem (15°33'15" : 73°56'30") and Gauntana (15°32'45" : 74°1') on the other. The total area covered is of about 50 sq.km. The Bicholim township is more or less centrally situated in the area.

The Sirigao-Bicholim deposit forms a prominent hill-range

which extends northwestwards from south of Bicholim town through Lamgao (15°35'30" : 73°56') and Redeval (15°36' : 73°56') upto Sirigao village. In the southeastern end of the area, near Sanquelim town, there is another rich deposit of iron ore, locally known as Sanquelim deposit. In addition, there are also some minor iron ore workings at Sarvon (15°34'30" : 73°56'), Nanora and a few abandoned pits which were also visited but not considered worthwhile to include in this work. The deposit generally contributes three different types of iron ores viz., hard, friable and powdery. Occasionally, they have minor association of manganese ores.

Unfortunately, widespread and deep lateritization in the area has affected the rock exposures to such an extent that it is difficult to recognise the original character and structure of the exposed rocks. Only in the deeply cut mine workings comparatively fresh rocks and ores provided more useful geological data for this investigation. Road and nala cuttings with but a few exceptions are also not so deep as to expose fresh rocks. In general, good natural rock exposures in the area are so scanty that they thwarted systematic collection of geological informations.

TECHNIQUES OF INVESTIGATION AND PRESENTATION OF THE WORK

The techniques adopted for field as well as laboratory investigations were all guided by the demand of the problem.

Broadly, the present study was based on the following methods of investigation and techniques :

1. Field techniques :
   (a) Reconnaisance survey followed by the preparation of a gelogical map of about 50 sq.km around the area on a scale 1 : 25,000.
   (b) Preparation of a detailed surface geological map of Sirigao mines on a scale 1 : 2,4000 with the help of telescopic alidade and plane table.
   (c) Examination of field characteristics of the country rocks and systematic collection of rock samples for thin section study.
   (d) Close examination of the iron ores in different mine sections and selection of ore samples for ore-microscopic study and chemical analysis.
2. Laboratory techniques :
   (a) Thin section study of phyllites, banded ferruginous quartzites, quartzites, and some basic instrusives.
   (b) Examination under ore-microscope of about 60 selected samples of polished ores.
   (c) Friable and powdery ores were run through an Isodynamic magnetic seperator to seperate the more magnetically susceptible minerals from the ores.
   (d) Sieve analysis of a few samples of powdery ore.
   (e) The hard, friable and powdery iron ores and a few ferro-manganese ores were analysed by the Geo-Chem

laboratories of Bombay. The results obtained from them are used in this work.

The entire work is presented in the following order :

i) Introduction
ii) Geology of the area
iii) Petrography and metamorphism
iv) Ore deposits
v) Structure
vi) Mineragraphy and paragenesis
vii) Genesis
Summary and Conclusion

MINING

The mining of iron ores in Goa was initiated on a small scale in 1908 by a group of French mining engineers. They also carried some prospecting work, as could be seen even today in a number of prospecting tunnels in Bicholim mines. The mining activity ceased soon after 1908 and revived again in 1949. Since then the mining industry in Goa has been progressing (see Varma et al., 1967). The enterprise enjoyed a boom in 1957 and onwards with increasing demand of Goa's iron ores by the Japanese steel industry. With the help of Japanese mining engineers, Chowgule and Co., a local mining concern, mechanised their Sirigao mines in 1963.

Both the Sirigao-Bicholim and Sanquelim deposits occur along

the ridge slopes facing northeast or southwest. Initial open cast mining requires the opening of the faces of the ridge from which the laterite overburden is removed first. In a systematic mining operation, faces are progressively cut backwards in the form of successive benches to reach the ore zone. The height of each bench varies from mine to mine. In the highly mechanized Sirigao mines benches are vertically five meters apart with correspondingly greater bench width to allow laying of mine roads. On the contrary, in unsystematic prospecting and inadequate information on the extent and reserve of ore deposit resulted irregular mining at many places in the area. A portion of the Sirigao-Bicholim lease belonging to Bandekar and Co., may be cited as an example of above fact. All the present major workings in the area are open-cast.

PREVIOUS INVESTIGATIONS

A review of the few available previous geological literature on Goa revealed that the region had failed to receive due attention of the earlier workers, probably because the Portuguese government did not encourage any traditional geological study. The Geological Survey of India has not yet published any report of the work done by its officers since about 1963.

Fermor (1909, p.980-985) first referred to the nature and mode of occurrence of manganese ores of Goa but mentioned nothing about the iron ores. In his account on the correlation of the

ancient schistose formation of Peninsular India, Fermor (1936, p.104) stated that

> The Portuguese territory of Goa has never been systematically surveyed geologically so that it is not known whether the Dharwar rocks of that track belong to the Castle Rock band or to an additional band ...

Krishnan (1952, 1955), while dealing with the iron ores of India, mentioned only about the occurrence of iron ore deposits at Bicholim, Goa. But he did not enter into the details of the subject.

Dhepe (1953) in his paper outlined the geology of Goa giving some information regarding the mode of occurrence, grade, mining, etc. of the iron and manganese ores.

D'cruz (1963) described briefly the geology, mining and marketing of the iron and manganese ores of Goa. He further referred to the occurrence of Dharwar schists, in addition to the pre-Dharwar granite and some post-Dharwar basic intrusives, laterite, etc., in Goa.

Souza (163) discussed in two seperate papers the mining of iron ores in Goa and the geomorphology of the territory.

Recently, Varma et al., (1967) have given an outline of the geology, in addition to the physical and chemical nature of the iron ores of Goa.

The publications, referred to above, obviously show that the geological investigations done so far on the iron ore deposits of Goa and particularly, of Bicholim and its adjacent

areas are not only incomprehensive but also have little bearing on the structure, mineralogy and genesis of the ore deposits under study.

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Chapter II

GEOLOGY OF THE AREA

GENERAL REVIEW

Broadly speeking, the geological set up of the Union territory of Goa does not differ much from the adjacent state of Mysore (see Rama Rao, 1940). As a matter of fact the Precambrian rock formations of Goa are believed to be the northwestward continuation of the Mysore Dharwars. One of the earliest accounts of the geology of the territory was given by Pascoe (1950, p.93) who stated :

> The Portuguese province of Goa consists mainly of Dharwar rocks, very largely obscured by a covering of laterite. Gneissose rocks may occupy some of the hills and have been noted in the railway cutting at Dudh Sagar railway station. Among the rocks assignable to the Dharwars the following have been recorded : quartzite, magnetite, quartzite, haematite quartzite, limonite quartzite, sericite quartz schist, fine-grained biotite-quartz schist, phyllite, fine-grained grey limestone and basic igneous rocks. The limestones are thought to occupy the highest position in the local sequence. The beds are traversed by quartz veins.

Phyllites occur over a large part of the area under investigation. Sometimes they enclose banded ferruginous quartzites with occasional workable iron ores at several localities of which, Sirigao, Bicholim and Sanquelim have large deposits of iron ores. Most of these country rocks are covered extensively by a blanket of laterites which generally vary in thickness from place to place. The maximum thickness of the

laterites recorded from the area is about 30 m. They have generally a greater thickness over the phyllites than over the ferruginous quartzites. The other superficial deposit encountered at several places in the area is alluvium dropped by a network of sluggish streams and their tributaries.

The phyllites as well as the ferruginous quartzites in the area under review have the same NW-SE strike and north-easterly dips as that of the other Precambrian rock formations of Goa and also of the Dharwar schists of Mysore in the south.

The rocks are devoid of any such recognisable non-diastropic sedimentary structures as ripple marks, current bedding, etc. However, only bedding lamination is such a structure which is retained by the ferruginous quartzites. The phyllites as well as the ferruginous quartzites are isoclinally folded with their fold axes trending NW-SE. The ferruginous quartzites are represented by two major outcrops, one at Bicholim and the other near Sanquelim, at a distance of about 7 km from the former. Both of them have a general NW-SE trend and occupy a prominent ridge each at Bicholim and Sanquelim. Only the northwestern part of the Bicholim outcrop in the neighbourhood of Sirigao has developed an 'S'-shaped bend as a result of drag folding. The general appearance of the Sanquelim outcrop is 'V'-shaped. Besides these, a few more small and insignificant outcrops of ferruginous quartzites were encountered in the area but they are not shown on the map.

The lithological characters of the phyllites and quartzites

indicate that both of them are low grade regionally metamorphosed rocks.

The ferruginous quartzites had, however, undergone profound residual concentration as a result of which large deposits of iron ores were formed in these rocks.

STRATIGRAPHY

Newbold (1844, p.145) was one of the earliest known geologists to examine the Precambrian rocks of Mysore state in South India. He applied the term '' hypogene series '' to the crystalline complex of South India and included in this series schistose and gnessic rocks.

Later, King (1872, p.36) studied those rocks and grouped them separately with the '' Altered or transition rocks '' and '' crystalline rocks ''. He introduced the former group as '' Kadapah '' and '' Karnul '' and the latter as '' gneissic series ''.

Foote (1876, p.41) sub-divided the rocks of the '' gneissic series '' of King into two, viz., 1) the '' granitoid '', highly crystalline and massive and 2) '' schistose'', the less crystalline and often highly foliated and distinguished five principal varieties of the '' schistose '' group. They are hornblende schists, micaceous schists, chlorite-schists, hematite schists and talcose schists. In a later work, he (1866) proposed the name '' Dharwar '' to these Precambrian schistose group of Mysore.

It was Fermor (1909,p.1120), who made a general application of the term '' Dharwar '' in Indian stratigraphy and stated :

> The term Dharwar is a comprehensive one and can be applied to all the sedimentary schists lying below the Eparchaean unconformity. It is extremely probable that there are many breaks in the schistose formation in different parts of India, but we can hardly hope to be able to correlate such breaks in different parts of India with any degree of certainty, and hence must make use of a general term to include the whole of this series of schists without taking any notice of the breaks. The term 'Dharwar' seems to be the term to use thus.

Although, no further account of the geology of Goa is available from the previous literature yet there is a general agreement that a major portion of the territory is composed of rocks belonging to the Dharwar age. It is, therefore, obvious that no serious attempt whatsoever was made to suggest any definite correlation of the Precambrian rocks of Goa with any other similar rock formation of India.

The most common Precambrian schistose rocks in the area of investigation are phyllites. Several lentiform banded ferruginous quartzites and some non-ferruginous massive quartzites are interbedded with the phyllites. A number of metadolerite and dolerite dykes occur in the phyllites on the east and north of the area. Locally, the banded ferruginous quartzites have great economic importance because of their large reserves of iron ores.

The sequence of rock formation studied in the area under review is presented as follows :-

	Recent	Alluvium
	Sub-recent	Laterites
	Deccan Trap?	Dolerite
Precambrian :	Intrusive	Metadolerite
	Scistose formation.	Phyllites with banded ferruginous quartzite and some massive quartzites.

Highly lateritized phyllites extend from the south of Dudonem and Gauntana on the south of area to beyond Nanora, Ladpem ($15^{\circ}37'30"$: $73^{\circ}57'30"$) and Poriem on the north of Bicholim and Sanquelim (Fig.3).

In this connection it may be mentioned here that these phyllites belong to the northwestern part of a northwesterly plunging regional syncline which Gokul (1963) mapped in north-eastern Goa. The western limb of the syncline extends from Capora river, further north of the area, to south of Madei river on the south (Fig.2), where it joins the eastern limb of the syncline. This eastern limb is narrower than the western limb and consists of phyllites with some interbedded limestone and banded magnetite-quartzite on its northeastward extension. On this basis Gokul concluded that 'western strip' and 'eastern strip' of the phyllites in the northeastern portion of the territory form a major syncline between Mandovi river on the west and Nagargao ($15^{\circ}33'45"$: $74^{\circ}9'30"$), Dongurli ($15^{\circ}36'15"$: $74^{\circ}8'45"$), Choraundem ($15^{\circ}37'45"$: $74^{\circ}7'30"$) on the east. The axis of the

syncline roughly passes through Zormen (15°34'30" : 74°6'30"), Querim (15°36'15" : 74°4'30") and Siruli (15°37'30" : 74°4'). The closure of the syncline lies between Volpoi (15°32' : 74°8'15"), and Nunuz (15°30'30" : 74°7'30"). Gokul (1963) placed the phyllites with associated banded ferruginous quartzite, massive quartzite and limestone at the base of a number of other rock types, the succession of which in ascending order is quartz-chlorite-sericite schits, altered ultrabasics, granite gneiss, pegmatites and vein quartz, basic intrusives, Deccan trap, laterites and alluvium. He further classified the underlying phyllites and quartzites with the Dharwar schists.

Dhepe (1953) and D'cruz (1963) have also mentioned a more or less similar sequence of the Precambrian formations of Goa. D'cruz, however, placed the granite and granite gneiss below the Dharwar schists while Dhepe considered them as post-Dharwars, which may be the correct position.

LITHOLOGY

An account of the lithological characters of the various rock types encountered in the field is given below.

Phyllites

Extensive lateritization of the phyllites left only a few isolated outcrops wherefrom some fresh or partly altered rock samples could be collected. None of the phyllites, fresh or

weathered, show any trace of bedding lamination from which the relation between the schistosity and bedding-plane could be ascertained. Schistosity is rather well-developed in most cases. The rocks commonly have pinkish brown or brownish grey colour. Occasionally, however, there are some pale grey to greenish grey varieties of phyllites.

About a kilometer west of Curchirem (66.43 m) a few thin bands of pale greenish-grey or brownish-grey phyllites crop out. The outcrops are mostly fresh in the stream sections but on the banks they are covered by laterites. The fresh rocks are distinctly foliated but that does not give to the rock a silky sheen and moreover, along their foloiation they have a little tendency to split into thin slices. Joint and fracture planes are all stained dark brown due to infiltration of iron hydroxides.

Another small outcrop of phyllites in a much weathered state is exposed under a thin mantle of laterite along the Piligao-Bicholim road section about 1.6 km noth of Piligao ($15^{o}33'30''$: $73^{o}56'$). The junction between the overlying laterites and underlying phyllites is graditional. Due to the weathering the rock became very soft and rendered ocherous or clayey. Similarly weathered pinkish brown or brownish white phyllites were also observed in the tunnel No.4 of Sanquelim mines where they occupy the foot wall of the ore body and also in a few other open cast mine sections, particularly where the iron ores have been worked out and the foot-wall rocks were exposed. Thin bands of powdery

silica or small pockets of shaly or powdery iron ores are commonly associated with these phyllites.

A few thin strips of pale green to greenish grey phyllites associated with the common variety of phyllites, mentioned above, were encountered in the river Valvota near Poriem. The rocks are hard, compact and finely crystalline. Schistosity is developed but not so distinctly as the common variety of phyllites. These thin greenish phyllites appear to be a local variety which is restricted in occurrence only in the northern part of the area.

Banded Ferruginous Quartzite

The banded ferruginous quartzites do not constitute a separate horizon but occur as lentimular intercalations in the phyllites. Their outcrops range in width from a few meters to as much as 80 m and in length from a few meters to even upto 7 Km as in the case of Sirigao-Bicholim outcrop. Due to their greater resistance to weathering and erosion they generally form prominent ridges on which most of the present iron ore workings of Bicholim and Sanquelim are located. The ridges generally follow the NW-SE strike of the quartzites and also of the enclosing phyllites. The banding in the quartzites is due to the presence of parallel alternate dark ferruginous and white cherty quartzite laminations which are attributed to the original depositional feature of the rock. The ferruginous bands consist mostly of granular magnetite and scaly hematite. In most cases these bands are

very thin, regular and persisting. The individual bands varies in thickness from 0.5 to 3 mm or slightly more. The quartzites which are either bodily associated or occur in close proximity to the ore deposits are generally characterized by thinner bands (Plate I, fig.1), which even after folding have the same thickness. On the contrary the quartzites in localities away from the ore-deposits have either thicker bands (Plate I, fig.2) or none. The weathered variety of thinly laminated quartzites developed a tendency to break up easily into thin slices along their bedding planes and some along joint planes. Generally the rocks are fine-grained and compact.

Since the ferruginous quartzites happen to be the source rock of the iron ore deposits in the area, evidences of supergene alteration and concentration of iron ores from the initial to the final stage are present in them. Frequent preservation of the minor secondary structures, in addition to the bedding laminations in the iron ores, is a positive evidence of replacement of the parent rocks as a dominant process of ore formation in this case.

There are some minor bodies of massive or thick bedded quartzites which occur impersistently in the phyllites. A few isolated lenses of such quartzites occur along the upstream course of Bicholim river near Ona ($15^{o}37'30''$: $73^{o}57'30''$), Nanora and in a few other localities in the area. Their strike and dip are generally the same as that of the phyllites. No

deposit of iron ores has so far been reported from these quartzites. The massive variety of these quartzites is dark grey in colour, highly siliceous, fine-grained, hard and compact. Colour is variable in the case of thick-bedded quartzites which are less siliceous than the massive variety but greater than the ferruginous quartzites.

Basic Intrusives

The schistose rocks of the area are intruded by a number of dolerite dykes. Some of the dykes are over 6 m thick. The general strike trend of majority of the dykes range from NNE-SSE to NW-SE and the dip nearly vertical. The contacts of these dykes with the phyllites are usually recognisable except when completely covered by laterites. A number of such dykes occur between the Sanquelim bridge and Poriem on the river Valvota. Their outcrops are impersistent and often concealed in the laterites. Two outcrops of the dykes, of which one is bouldery, were also encountered about a Km southeast of Maulingaem (138.57 m). The rock is dark green to greenish grey in colour, hard and medium to fine-grained (Plate I,fig.3). The suite may possibly be of Deccan trap age. There is another suite of dykes that have some effect of metamorphism due to which they have been foliated to some extent. These foliated basic dykes, introduced here as metadolerite which may be older than the unaltered dykes mentioned above.

Laterites

The laterites, which range in thickness from a few meters to about 30 m, in the area are believed to be the products of supergene alteration of phyllites and the associated ferruginous quartzites. However, the ferruginous quartzites are comparatively less affected by lateritization than the phyllites. The laterites, which are derived from phyllites, are moderately aluminous and show typical pisolitic and vermicular structures (Plate I, fig.4). Their colour varies from light pink to light yellow, cream or pale brown. Generally they include small pockets of white or cream-yellow clayey materials. Occasional presence ofalimonite crust or coating made them harder than the normal varieties. Laterites that formed over the ore body are generally brick-red in colour, porous and highly ferruginous. They frequently include small crystals of secondary quartz. Locally the aluminous laterites are extensively quarried for use as road and building materials.

The aluminous laterites of the area were generally found occupying the flat-topped and low-lying hills, while the ferruginous ones occur as capping on the iron ridges and other prominent hills, as for example their occurrence on the Bicholim-Sirigao ridge and Sanquelim hill (97.03 m) can be cited.

GENERAL STRUCTURAL FEATURES

The nature of the present work necessitated study of some local structural features which have important bearing on the structure of the ore deposits. A fair attempt is made to present here the author's own observations on the general structural features of the area.

The hilly tract of Northern Goa begins from beyond the northeastern boundary of the area. The R.L. of the two prominent ridges in the region which are located at Salali ($15^{\circ}34'45''$: $74^{\circ}5'$) and Morlemgod ($15^{\circ}35'$: $74^{\circ}4'45''$) are 616.61 m and 573.75 m respectively. The trend of these ridges is roughly NNW-SSE which is more or less same as the regional strike of the Precambrian schistose rocks of the area under study, as well as to those of the neighbouring state of Mysore (see Krishnan, 1953).

Since widespread lateritization has greatly obliterated the structural details of the outcropping phyllites much of the useful data pertaining to the structure of the Precambrian rocks of the area were obtained from the banded ferruginous quartzites which on account of their greater resistence to weathering could retain many interesting structures.

From Sirigao, on the northwest, to Sanquelim on the southeast of the area, the strike of the phyllites is roughly NW-SE with northeasterly dips ranging from 30° to 50°. The structural trend of associated ferruginous quartzites is also

the same as the phyllites but usually they have higher northeasterly dips.

Therefore, most of the studies relating to the structure of the area were concentrated on the ferruginous quartzites of Sirigao-Bicholim and those of Sanquelim area. The structure of these iron-bearing ferruginous quartzites has been described in greater detail while discussing the structure of the ore deposits later in this text. However, it may be remembered that there are two different outcrops of ferruginous quartzites separated and surrounded by phyllites. The one which extends from Sirigao to Bicholim, is about 7 Km long and the other which occurs about 400 m northeast of the former has a length of about 1.75 Km. Both these outcrops have a general NW-SE strike. The general direction of dip and strike of a greater part of the longer Sirigao-Bicholim outcrop, between Sirigao hill (161.54 m) and Bicholim, remains unchanged except for some local variation. The amount of dip in this part generally varies from 45° to 80° NE. The northwestern part of the same outcrop takes an 'S'-shaped bend between Sirigao hill and Sirigao (Fig.3). From the Sirigao hill the outcrop swings round from NW-SE to almost N-S within a distance of one km beyond which it rebends and restores its general NW trend. Finally, the outcrop disappears below an alluvium at a distance of about 1.5 km NW of the last bend.

The Bicholim-Sirigao outcrop represents a northwest plunging isoclinal anticline, the limbs and axial plane of which dip northeastwards. The nose of this anticline is about 0.5 km

west of Sirigao where it plunges at an angle of 20° NW. The S-shaped outcrop of quartzites near Sirigao represents a drag fold which was most probably formed due to continuing differential shear movements accompanying the earlier deformation (see Narayanaswami, 1959, p.88). The axes of the cross-folds are sub-parallel to the axis of earlier isoclinal fold and their plunges are in the same general direction as the plunge of the latter. Narayanaswami (1959, 1966) also described several types of such drag folds affecting the folded rocks belonging to the nearby Dharwar rocks of Mysore and similar other Indian Precambrian formations elsewhere in the country.

The smaller outcrop of ferruginous quartzites, which occurs about 400 m northeast of the main Sirigao-Bicholim outcrop, appears to be the much eroded northeastern limb of the Sirigao-Bicholim anticline. The limb now stands separated from the southwestern limb of the anticline by phyllites and runs almost parallel to the latter. Its strike is NW-SE and dip varies from 50° to 60° NW.

The other outcrop of the ferruginous quartzites at Sanquelim in the southeastern part of the area, extends over a distance of about 2.5 km from west of Valvota river to Gauntana with a general NW-SE strike and northeasterly dips varying between 50° and 80°.

The southern part of this outcrop between the Sanquelim hill (97.03 m) and Gauntana bifurcates into two narrow outcrops

of ferruginous quartzites separated by a narrow strip of phyllites. Amount and direction of dips in this part are also consistent with the rest of outcrop.

Thus, between Valvota river and Gauntana, the ferruginous quartzites form a narrow 'V'-shaped outcrop which also represents an eroded isoclinal anticline plunging 30° NW. Its two limbs correspond to the two narrow outcrops of quartzites between Gauntana and Maulingiem ($15^{\circ}33'15"$: $74^{\circ}1'$). The narrow strip of phyllites outcropping between two anticlinal limbs was exposed as a result of erosion of a greater part of the crest of the anticline.

It may now be summarily stated that all the major outcrops of banded ferruginous quartzites and the related phyllites in the area were intensely folded into northeasterly dipping and northwesterly plunging isoclinal anticlines. The northwestern anticline was offset by a drag fold which bent the outcrop near Sirigao in the form of 'S'. It is also obvious from the nature and relative position of the two outcrops of ferruginous quartzites that they were folded in an en echelon pattern into two anticlines plunging in the same direction. Since, these two folds occur in the western limb of a northwesterly plunging regional syncline, they have been identified as left-handed en echelon folds. Similar types of en echelon folds were also reported from several other places in the Precambrian terrain of South India (see Narayanaswamy, 1959).

CORRELATION

Rama Rao (1940) classified the Mysore Dharwars into three divisions viz., lower, middle and upper, which lie separated from one another by two distinct horizons of conglomerates. No Precambrian conglomerate was reported from Goa by any one of the previous workers. The present worker also did not encounter any such horizon in the area mapped by him. But, the presence of banded hematite-quartzites with iron ores, lithological homogeneity, structural trends and the grade of metamorphism of the Precambrian schistose rocks of Goa provided satisfactory criteria for correlating them with the Dharwars of the adjacent state of Mysore. On identical grounds Fermor (1936) and Krishnan (1960) attempted to correlate the Precambrian schistose rocks of Singhbhum, Orissa and Madhya Pradesh with the Mysore Dharwars. Krishnan (1960, p.101) remarked that the term Dharwar system

> serves to designate the schistose rocks older than the Eparchaeaan unconformity and to indicate the approximate homotaxial relationship of these formations in various parts of India.

Dunn (1940, p.308-309) while dealing with the stratigraphy of south Singhbhum expressed that it was inadvisable to correlate the schistose rocks, scattered over different parts of India, with the little known rocks of Dharwar type area. He preferred to retain the local names for the Precambrian rocks in different parts of India, and to restrict the term Dharwars to the schists of south India. A similar idea was also expressed by Pichamuthu (1963, p.86 ; 1967, p.6).

Rama Rao (1962, p.34-35) pointed out that the correlation of widely separated exposures of unfossiliferous schists on lithological similarities is usually unsatisfactory and unwarranted. Radhakrishna (1967, p.106) stated that

> There is nothing to warrant the supposition that the Dharwars were very extensive or that all the Dharwar patches in the Peninsula were once connected.

He further suggested that (p.109)

> The term Dharwars should be restricted to designate the archaean schists of only Mysore. The term Archaean is good enough to include the succession of schistose rocks of different areas like the Eastern Ghats, the Satpura and the Aravallis which may represent only a section of Dharwars or may be entirely different.

From the above consideration it is evident that there is still some difference of opinion regarding the stratigraphic position of these schistose rocks from different parts of India and their suitable correlation.

So far as Goa's Precambrian geology is concerned, the statements made by Dunn (1940), Rama Rao (1962), Pichamuthu (1963, 1967) and Radhakrishna (1967) do not probably hold good, partly because of the fact that the territory of Goa is not wide apart from the Dharwars of the type area in Mysore and partly due to lithological, structural and metamorphic similarities between the schistose rocks of Goa and atleast those occurring in the northern part of the Mysore Dharwars.

A possible explanation for the absence of any conglomeratic horizon in Goa may be that the two horizons of conglomerate in

Mysore are probably of local occurrences as they are restricted only to the Dharwar-Shimoga and the Gadag-Chitaldurg schist belts of northern Mysore. More justification for the above view was given by Rama Rao (1940, p.85-86) as follows :

> We cannot say whether the whole of the Dharwar system of Mysore can be correllated with any single series... This depends upon whether the two zones of unconformities recognised in the Dharwar Schists in Mysore are widespread and occur at the same horizon in the other archaean tracts of India or whether they are only local and confined to Mysore.

Fermor (1936, p.192), while discussing the correlation of the schistose formations of Singhbhum (Bihar) and Orissa, was first confused whether the term '' Dharwar '' should be applied to the '' old metamorphics '' or to the upper '' Iron Ore-Series '' . At first, the question seemed to be difficult for him to answer due to the presence of quartzites, mica and hornblends schists in both the series, but later on, he was guided by the presence of iron ore formation in one of them for the purpose of correlation. He concluded that

> The important masses of hematite-quartzite and hematite ore that occur in the Iron-ore series seem to provide the deciding factor in favour of the Iron-ore series being the equivalents of the Dharwars of South India.

He also suggested correlation on lithological grounds of the hematite-quartzite rocks and iron ore deposits of Chanda and Durg, Madhya Pradesh with the hematite deposits of Goa, Sandur and elsewhere in the Dharwar-Mysore-Nellore province and the Iron-Ore series of Singhbhum (p.155).

Krishnan (1960, p.154) recorded crystalline limestone, manganese-bearing rocks and iron ores from several Precambrian schistose areas of India. Such associations, according to him, can be satisfactorily used as a criterion for the purpose of correlation on the assumption that at a certain period of earth's history, such special types of sediments were deposited. He considered the banded ferruginous rocks and the iron ores, which characterize the Iron-Ore series of Chota Nagpur and Bastar, the Sakoli Series, the Chilpi Ghat Series, the Middle Dharwars of Mysore and the schistose rocks of Salem as broadly equivalent. However, in his concluding remarks he added that (p.156)

> The complexity of the Archaeans prevents us from attempting anything more than the above broad indication of correlation.

In the tabular correlation scheme (Krishnan, 1960, p.155) the Middle Dharwars of Mysore with the banded ferruginous quartzites were shown as equivalent to Bailadila Iron-Ore Series and the Sakoli Series of Bastar, Madhya Pradesh, and the Iron-Ore series of Bihar and Orissa.

It is obvious, therefore, that in the previous work considerable emphasis was laid on the lithology and presence of iron ore horizon for the purpose of correlation of widely separated Archaean terrains of India.

Rama Rao (1940, p.37), in his middle division of Mysore Dharwars mentioned a number of lithological units of which iron stone, limestone, argillites, quartzites and conglomerates

predominate. A number of these rocks is more or less identical to the Precambrian rock groups of Goa except the conglomerates. Among all the rock types, banded ferruginous quartzite is the most characteristic member associated with the phyllites of Goa, and which may be taken as a marker horizon for the presently suggested correlation.

Rama Rao (1940, p.57) further mentioned that the threefold division of Dharwar schists can only be recognised with certainty in the northern parts of the Mysore state. Therefore, it would not be unwarranted to presume that the basin of deposition during the Middle Dharwar period extended further north of Mysore into the territory of Goa where more or less similar rock units were encountered (see Radhakrishnan, 1967, p.104).

The other points of some significance to be stated in this connection are the similarities of lithological character of banded ferruginous quartzites, regional structure and the grade of metamorphism between the Dharwar schists of northern Mysore and the Precambrian schists of Goa.

The Dharwar schists of Mysore have a more or less NNW-SSE regional strike extending uniformly for about 600 Km from north to south. A larger part of the northern extremity of the Dharwars is limited by the Deccan traps which cover a large part of the country further north (Krishnan, 1953, p.5 ; Radhakrishnan, 1967, p.104). The regional strike of the phyllites and banded ferruginous quartzite of Goa is much the same as that

of the Dharwars of Mysore. Additionally, the en echelon drag folds, which are so common in Mysore, are also reported from the area under review.

The typical iron ore bearing Dharwar banded hematite - quartzites, associated with argillitic and chloritic schists of north Mysore, are finely banded consisting of ferruginous and siliceous layers (see Rama Rao, 1940, p.24). They are very much similar to the iron formations of Goa which occur in chlorite phyllites.

Further, it is a well-known fact that the grade of metamorphism of the Dharwar schists of Mysore progressively decreases from the south to north. The northern part of low grade metamorphism is characterised by the presence of chlorite schists, while in the southern part they have reconstituted developing kyanite, sillimanite, garnet, etc. (see Rama Rao, 1940, p.57-58 ; Krishnan, 1960, p.104). Complete absence of rocks of high grade metamorphic facies anywhere in Goa in association with the chlorite phyllites makes the rocks closely comparable to the low grade chlorite-schist facies of northern Mysore.

In the light of above statement comparing the Middle Dharwars of northern Mysore with the Precambrian schistose rocks of Goa on the basis of their lithological similarity and comparable grade of metamorphism, structural units and iron ore association, the author has enough justification to believe

that they are not only stratigraphically equivalent but also continuous. Hence the phyllites, banded ferruginous quartzites and the associated iron ores of Bicholim and Sanquelim should also be regarded as a part of the Dharwars irrespective of their territorial limitations.

Chapter III

PETROGRAPHY AND METAMORPHISM

Among the metasedimentary rocks of the area concerned, phyllites are the most widespread. They are, however, in a highly weathered state and have largely been altered into laterites, sometimes of considerable thickness. This was in fact a serious handicap in the field for any systematic attempt to collect fresh samples of phyllites for petrographic studies. However, as far as practicable, attempts were made to pick up the desired samples from the few outcrops of phyllites which were still fresh or weathered partly. Collection of rock samples from other formations, such as ferruginous quartzites, dyke rocks, etc., did not however, pose such a problem.

The following important rock types have been chosen for petrographic studies :

i) Chlorite phyllites
ii) Calcareous phyllites
iii) Banded or ferruginous siliceous quartzite
iv) Basic rocks

PETROGRAPHIC DESCRIPTION

Chlorite phyllites

Most of the minerals composing the chlorite phyllites are too small to be distinguished magascopically. Under the microscope the rocks appear to be schistose and fine-grained with some porphyroblasts of quartz and felspar (Plate II, fig.1). The finer grained minerals are quartz, felspars, flaky mica and chlorite.

Grenular or scaly opaque iron oxides are randomly distributed throughout the ground mass. Zircon and tourmaline, probably detrital minerals, occur very rarely. Very minute crystals of apatite and zircon also occur as inclusions in the porphyroblasts of felspars and, less commonly, in quartz.

Quartz.- The porphyroblasts ofquartz are mostly rounded to subrounded (Plate II, fig.2) with some of them slightly elongated. The longer axes of such grains are usually oriented parallel to the foliation direction of the phyllites (Plate II, fig.1). Some of the prophyroblasts are fractured. Due to recrystallization most of their original crystal boundaries were obliterated beyond any recognition. Strain shadow is a characteristic feature of this quartz. Sometimes aggregates of finer-grained quartz occur locally. The grains have sutured boundaries along which they are interlocked (Plate II, fig.3).

Felspar.- Albite happens to be the common variety of felspar in the phyllites. Porphyroblasts of albite are quite abundant and sometimes their quantity seems to be a little higher than that in the normal pelitic rocks. Both twinned and untwinned varieties of albite are present, of which the untwinned ones are predominant. Their shape varies from anhedral to subhedral. Minute inclusions of micas, chlorite, apatite, etc., are generally abundant in the albite and in a few cases inclusions are so much crowded that a sort of sieve structure is formed (Plate II, fig.4).

Flaky Minerals.- Aggregates of flaky minerals like muscovite, chlorite and sericite are so common in the phyllites that their presence has made the rock cleavages conspicuous. Biotite is

very rare. Occasionally, these flaky minerals are segregated along distinct bands (Plate III, fig.1). Some of the flaky minerals are deformed and bent around the porphyroblasts of quartz and albite. Sericite and muscovite also occur as inclusions commonly in albite but rarely in quartz.

Opaque Minerals.- Magnetite and hematite are the two opaque minerals associated with the phyllites. The shape of magnetite grains is either octahedral or elongated whereas hematite occurs either in granular or scaly form. Both of them are distributed randomly throughout the thin section.

Zircon.- There are a few minute crystals of zircon with rounded to subrounded shape, which indicates original detrital nature of the mineral.

Calcareous phyllites

This variety of phyllites is very fine-grained, comparatively more compact and hard, and less distinctly foliated than the chlorite phyllites. The rock is essentially composed of some coarser-grained calcite, felspar and quartz which are enclosed in a sub-microscopic matrix composed of finer-grained quartz, felspars, micas and chlorite. Iron oxides are distributed throughout the sections. There are also a few grains of zircon.

Calcite.- Calcite occurs quite frequently as irregular aggregates of crystals which are mostly subhedral to anhedral (Plate III, fig.2). Sometimes, the crystal aggregates form imperfect segregation bands. Change of relief is well-marked in calcite and often its crystal boundaries and cleavage partings are stained brown due to alteration.

Quartz.- The quartz porphyroblasts are so arranged that their major axes are parallel or subparallel to the foliation trend of the phyllites. The porphyroblasts invariably display strain shadow and are recrystallized but without showing any sign of outgrowth in thin section. A few of the porphyroblasts have retained partly their clastic nature.

Felspar.- Albite is the most common variety of felspar met with. The crystals are subhedral to anhedral and subangular to subrounded in shape. A few of the crystals show lamellar twinning but the rest is untwinned. The porphyroblasts are riddled with minute inclusions of micas, apatite and, rarely of zircon (Plate III, fig.3).

Flaky Minerals.- Muscovite and chlorite are the common flaky minerals. Sometimes, aggregates of these minerals are segregated into imperfect bands. Some chlorite and muscovite are also deformed and bent around quartz and felspar porphyroblasts as in chlorite phyllites. Biotite is rather subordinate and shows a distinct preferred orientation (Plate III, fig.4). Uniaxial mica occurs as inclusion in albite and quartz porphyroblasts.

Opaque Minerals.- Most thin sections have patches of dark brown iron oxides, confined mostly around calcite grains. In addition, there are some minute grains or scales of dark iron oxides.

Zircon.- Rarely a few rounded to subrounded minute crystals of zircon, probably detrital, occur in the rock. Minute crystals

of zircon also occur as inclusions in the felspar and quartz porphyroblasts.

Banded Ferruginous Quartzite

Usually, the banded ferruginous quartzite has alternating dark ferruginous and white siliceous bands (Plate IV, fig.1). Thin section study shows that the white bands are made up of cherty quartzite and the darker ones of iron oxides. The central part of each siliceous band has very little of iron oxides but as the adjacent dark bands are approached the proportion of iron oxides increases (Plate IV, fig.2).

The quartz grains in the siliceous bands are more or less equigranular, very fine-grained and occasionally cherty in nature (Plate IV, fig.3). On the average, grain size of quartz varies from 0.16 mm to 0.4 mm. The interlocking grains of quartz have sutured margins showing mosaic texture (Plate IV, fig.4). In ordinary light, grain boundaries are hardly redognisable due to the absence of any intergranular matrix. However, in certain cases, partial replacement or staining of the grain boundaries by a brown iron oxide, helps demarcate individual grains (Plate V, fig.1). Strain shadow effect is a characteristic optical property of this quartz. Quartz grains also have some dusty inclusions and specks of iron oxides.

The ferruginous bands consist mainly of euhedral to subhedral magnetite with subordinate amounts of quartz (Plate V, fig.2). In a few thin sections of these bands the amount of quartz is

is considerably high. The grain size of magnetite varies from 0.09 mm to 0.26 mm. Scaly and prismatic grains of hematite are often oriented parallel to the plane of schistosity which is crudely developed (Plate V, fig.3).

Basic Rocks

There are several outcrops of basic intrusives, including some metadolerites, which occur along the Bicholim and Valvota rivers north of Bicholim and Sanquelim townships respectively. In physical appearance, the younger dykes differ little from the older metadolerites, except in the grain-size. However, they differ markedly in their mineral constituents, textures, structures etc., visible in thin section only. It is on this basis that they have been classified as 1) metadolerite and 2) dolerite. The metadolerites are foliated and either epidote bearing or epidote free whereas the dolerites are unfoliated and may or may not have olivine among other mineral constituents.

Metadolerite.- The rock is commonly composed of plagioclase and hornblende with subordinate amounts of chlorite, sphene and iron oxides. Calcite and quartz are more subordinate. Frequently the rock exhibits granoblastic texture (Plate V, fig.4) but the blastophitic texture was also seen in some sections (Plate VI,fig.1). In general, schistosity is not so well developed. However, some rocks appear to be crudely foliated due to subparallel alignment of prismatic or streaky crystals of hornblende.

Plagioclase is commonly represented by the variety albite which is either subhedral or anhedral. Subhedral crystals

frequently show carlsbad and rarely albite twinning. Undulatory extinction may commonly be seen in the felspars. Plagioclases are partly altered into epidote and zoisite (Plate VI, fig.2).

Hornblende is either prismatic or fibrous with a pale green colour, faintly pleochoric from greenish brown to olive green colour. One set of imperfect cleavage in porphyroblastic hornblende is more common than two sets of rhombic cleavages. The actinolite and uralite which occur along with some chlorite around the hornblende crystals are alteration products of latter (Plate VI, fig.3). At places, intensely clouded patches, probably of original augite, are associated with hornblende. Both twinned and untwinned crystals of hornblende may be seen in thin sections.

Anhedral or subhedral epidote occurs in considerable amount in some thin sections while in others they are insignificant. The granular epidote commonly forms clusters in felspar while the subhedral one, which is comparatively large grain-size, occurs scattered or in aggregates (Plate VI, fig.3). Zoisite is less common than epidote. It occurs either as inclusions in albite or associated with epidote. Sphene, which is still rare, is granular. Some opaques usually form the core of sphene.

The groundmass is very fine-grained and almost submicroscopic. It consists of flaky amphiboles, chlorite, some granular felspar, epidote and zoisite. Sphene, quartz and calcite are uncommon.

Dolerite.- Megascopically both the varieties viz., olivine-bearing and olivine-free dolerites are dark grey in colour, medium-grained, hard and compact. The rocks show presence of lustrous plates of plagioclase and darker pyroxene.

Laths of plagioclase felspars and large plates of pyroxene are generally so disposed that they exhibit a typical ophitic texture (Plate VI,fig.).

Felspar is generally represented by andesine which is either lath-shaped, tabular or subhedral. Carlsbad twinning is by far the most common. A few of them are partially kaolinised due to which they have a clouded appearance (Plate VII,fig.1).

Pyroxene, when fresh, is represented by subhedral to anhedral augite. Occasionally augite alters to pale green and scaly aggregates of chlorite,formed particularly around its crystal boundaries. Both twinned and untwinned crystals of augite are present. The mineral has ordinarily one set of cleavage but in some cases two sets nearly at right angles are also seen.

Olivine, wherever occurs, is either anhedral or subhedral. Initial stage of alteration is indicated by the appearance of serpentine along irregular network of fractures in olivine. In a few cases alteration is so advanced that only a few relict patches of olivine remain in a mass of serpentine (Plate VII,fig.2). The other alteration product of olivine is iddingsite.

Both chlorite and biotite are generally associated with augite and less commonly with felspars.

METAMORPHISM

The mineralogical assemblage and petrographic characters of the phyllites and associated banded ferruginous quartzites of the area reveal that they are essentially metasedimentary rocks

originated as a result of regional metamorphism of ancient sediments composed largely of argillaceous materials, with the occasional presence of lenses of highly ferruginous psammites. Deformation and regional stress were probably responsible for chemical adjustment of the rocks to temperature and pressure (see Turner and Verhoogen, 1962, p.669). The petrography of the metamorphosed pelitic rocks suggests that their grade of metamorphism is low and equivalent to the chlorite zone (see Harker, 1960, p.209) or quartz-albite-muscovite-chlorite subfacies of greenschist facies (see Turner and Verhoogen, 1962, p.534). Metamorphosed basic rocks also testify to the above grade of metamorphism. The appearance of biotite in the calcareous phyllites evidently registers some advancement of metamorphism to the biotite zone of the greenschist facies (see Harker, 1960, p.214). The banded ferruginous quartzites are conspicuously free from any iron silicate or any other silicate mineral of metamorphic origin. The rock is typically composed of magnetite - chert with some specular hematite. The rock owes its banding to the original depositional feature of the sediment. In some quartzites a crude schistosity is developed on account of orientation of iron oxide minerals parallel to the strike of the bands. All these mineralogical, structural and textural features may be attributed to regional metamorphism of iron formation (see James, 1955) composed of almost equal proportion of ferruginous and silicenous materials. It is also evident from the mineralogical assemblage that the grade of metamorphism is low and belongs to the chlorite division of the greenschist facies (see Pascoe, 1950, p.80).

Chapter IV

ORE DEPOSITS

INDIAN IRON ORES

The Indian workable iron ore deposits are invariably associated with the Precambrian iron formation, commonly known as banded hematite-quartzite (see Jones, 1934, p.196) or banded hematite-Jasper (see Percival, 1931, p.190). The metamorphic equivalent of this rock is usually designated as quartz-magnetite rock (see Krishnan, 1952, p.503). Such deposits of iron ore occurs widely in the states of Bihar, Orissa, Madhya Pradesh and to a lesser extent in Madras, Mysore and Goa.

The Precambrian iron formation of Singhbhum district, Bihar, and Keonjhar and Bonai districts, Orissa, are known as Iron-Ore series (Jones, 1934, p.183). The major types of ore derived from them are massive, laminated, shaby and powdery. The hard and compact ore, which is largely confined to the surface, grades downward into shaby and powdery ore.

The ore deposits of Salem, Trichonopoly and Bellary districts of Madras and some of those of Mysore states are considered to have been derived from the metamorphosed iron formations commonly known as quarts-magnetite schists. They contain varying quantities of ferromagnesian silicates, in addition to magnetite and a certain amount of hematite. The other important deposits in the Mysore state comprise banded ferruginous quartzite which is similar to the banded hematite-jasper of Bihar and Orissa (see Krishnan, 1952, p.523,526).

In fact, all these iron ore deposits of India resemble closely each other in many respects and have many equivalents in the other parts of the world. Weld (1915, p.452) described the iron ores of India as follows :

> ... they are strikingly like the pre-Cambrian iron ores of Brazil. In fact one is almost tempted to apply the Brazilian term itabirite to the quartz-iron-ore beds, jacutinga to the laminated and micaceous ores occurring within phyllites, and canga to the surface accumulations of rubble-ore float and rich laterite.

So far as the iron ore deposits of Bicholim and Sanquelim, Goa, are concerned, it may be stated with some certainty that they also strikingly resemble the other Precambrian iron ore deposits of the country. These deposits produce three major types of ores viz., hard laminated, friable and powdery which are obviously easy to recognise by their physical state.

DISTRIBUTION

The major iron ore deposits of Bicholim and Sanquelim , north Goa, are separated from each other by about seven kilometers. The Bicholim deposit which occurs on the northwestern part of the area under review, also happens to be the richest deposit in the territory of Goa. This deposit emerges from the village Sirigao and Poira ($15^{o}35'45''$: $73^{o}54'15''$) on the northwest and after bending like an 'S' it continuously extends through a distance of about 7 km in a southeasterly direction upto south of Bicholim township (Fig. 3). There is another small ridge of iron ore, 400 m northeast of main Bicholim deposit, which is about 1.75 km long and known as Redeval deposit.

The Sanquelim deposit occurs on the southeast of the Bicholim deposit. It extends from northeast of Ozrim ($15^{o}33'45"$: $73^{o}59'33"$) to Gauntana. The richest part of this deposit seems to be the central region where active winning of the ore is in progress.

GENERAL CONSIDERATION

It has been already mentioned earlier that the mantle of laterites which spreads almost all over the area provides limited opportunity to study the surface geology. The outcrops of the ore deposits have also capping of ferruginous laterites of variable thickness, due to which the size and nature of the ore deposits were obscured. As a matter of fact the low grade lateritic iron ores of little economic importance overlie almost everywhere the higher grades of ore. This superficial ferruginous rock is an obstacle often encountered by the prospectors to reaching the main ore zone below. In most cases particularly for a small deposit the thickness of this lateritic cap is the primary consideration on which the workability of the deposit depends. Further, apparently there is a little physical difference between the laterite cappings on the ore bodies and those on the intervening phyllites. As such, excavations in the laterite zone without systematic prospecting become uncertain. This may be the main reason why many trenches and small quarries lay abandoned today throughout the iron belt.

It is, therefore, evident from what has been said above that

a zone of overburden is invariably present over the main iron ore bodies. The following laterites and ore zones could be recognised in the quarry sections of Bicholim and Sanquelim :

Ferruginous Laterite

The uppermost part of the deposits is highly lateritized and represented by hard pisolitic and vermicular ferruginous laterites, the thickness of which varies from 3 to 8 meters. The ores belonging to this zone have no economic importance because of their low iron contents.

There are several scattered boulders and small pockets of supergenic manganese ores found in the laterites. They are , however, insignificant in quantity and hence , uneconomic.

Iron Ore Laterite

Iron ore laterite largely consists of partially lateritized iron ores belonging to the upper part of the main ore zone lying immediately below the ferruginous laterite. Its relation to both overlying laterite and the underlying fresh ore is almost transitional. Large and small blocks or fragments of iron ore laterites, either poorly laminated or massive, are sporadically distributed. At places even the fine laminations of iron ore are retained by the laterite (Plate X, fig.2). But at other places, where lateritization is complete or reached an advanced stage, all such structures were obliterated. This laterite has also no commercial importance.

The laterite has also come scattered ores which are hard, compact and somewhat porous. Low in grade, dark brown to dull grey brown in colour. Small pockets or bands of yellowish white ochreous and clay materials are their common associations. Sp.gr. 2.8-3.4 . Iron content varies from 40 °/o to 55 °/o .

Ore Zones

There are more or less three graditional zones of hard, friable and powdery ores generally resting one below the other, which are economically very important. The continuity of these ore zones is fairly persistent although their total thickness varies widely from 15 m to 25 m. Either iron or ferruginous laterite is the usual capping over the ore deposits. The change from hard to friable ore is, however, distinct.

Hard Ore Zone.- The hard ore zone is almost as a rule covered by a mantle of laterite of variable thickness. Its field relation with the overlying lateritized ore zone (Plate VII, fig.3) and underlying friable ore zone is transitional. As such there is no clear demarcation between this zone and the overlying or the underlying zone. Its thickness varies from 2 to 6 meters. The hard ore extracted from this zone is locally known as lumpy ore.

Friable Ore Zone.- As it is followed from the surface downwards, the hard ore gradually becomes friable and remains so in a region which is defined here as a friable zone (Plate VIII, fig.1). With increasing depth the friable ore merges into a

powdery ore. It is, therefore, evident from the above facts that the friable ores occur in a zone which is transitional between the hard ore and the powdery ore zones. Minor pockets or bands of ochreous and clay materials are occasionally associated with this ore. Thickness of this zone varies from 3 to 5 meters.

Powdery Ore Zone.- Although the occurrence of small pockets of powdery ore in the hard ore is rare, as in Dampo's 5-Top Concessions, yet as a rule powdery ore zone occurs below the friable ores (Plate VIII, fig.2). The lower limits of this zone gradually merge into the footwall rock with decreasing proportion of iron ore. The thickness of the powdery zone varies from 10 to 15 meters. Often the powdery ores have intercalations of ochreous and clay materials, the proportion of which generally increases towards the base of the deposit. Increasing proportion of such intercalations provides an indication to the miners that the lower limit of the ore horizon may not be far below.

Most of the present mining activities at Sirigao, Bicholim and Sanquelim are confined to either friable or powdery ore zones (Plate IX, fig.1) except in few localities such as Bandakar's Sirigao mines, Dampo's 5-Top and 4-Bottom concessions on Sirigao-Bicholim deposit where mines are still operating in the upper hard ore zone.

NATURE OF THE ORES

It is evident from the foregoing description that physically the iron ores, mined from the ore horizon at Bicholim and Sanquelim

are divisible into three types viz., hard, friable and powdery. The grade of this composite ore is however, high and hence, it is considered to be one of the important economic deposits in the region.

There are also some scattered deposits of lateritized iron ores, some of which are associated with lateritic manganese ores. These ores are encountered above the main ore horizon at several localities in the area.

The physical characters of the various types of ores found at Bicholim and Sanquelim are described below :

Hard Laminated Ore

The iron ores, which are hard, compact and often thinly laminated, are introduced here as hard laminated ore (Plate IX, fig.2 and 3). They are finely crystalline, dark grey to bluish grey in colour particularly, in the case of freshly broken ores. Feebly magnetic and consist mainly of hematite and limonite with a subordinate amount of magnetite. Sp.gr., 3.0-3.3. The content of iron is 58 °/o to 62 °/o.

The coarsely crystalline hard iron ore with considerable amount of manganese oxides, as seen in Bandaker's Sirigao mines is also grouped with this variety of ore. It is rather restricted in field occurrence. Locally it is known as ferro-manganese ore (Plate X, fig.1) which is also somewhat rudely laminated and steel grey to dark bluish grey colour, hard, compact and soils the finger black. The major mineral assemblages in this ore are hematite, magnetite and pyrolusite.

Friable Ore

The ore is soft, friable and finely laminated. It has a greater tendency to break up easily into thin parallel plates (Plate VIII, fig.1). Highly jointed varieties may be called biscuity ore which is commonly admixed with iron oxide powders. Usually they are fine-grained and somewhat porous. It is dark grey, bluish grey or reddish brown in colour and composed mainly of magnetite. Sp.gr., 2.7-3.0. Iron content 60 °/o to 64 °/o.

Powdery Ore

With depth friable ore becomes more and more porous and the quantity of powdery ore in it increases proportionately. Finally, the ore becomes entirely powdery and loose as a greater depth is reached (Plate IX, fig.1). This loose variety of ore is also known as 'blue dust' . Its laminations were also distinctly visible in the undisturbed portions of powdery ores. Powdery ores preserving such structures as bedding laminations, folds and even minor faults were also reported from Singhbhum and Orissa (see Dunn, 1941, p.368).

The ore is composed mostly of a fine, dark blue powder of specular hematite and magnetite. Quartz is subordinate in amount. Sp.gr., 3.2-3.5 . Iron content 62 °/o to 65 °/o.

Following are the results of screen tests of two powdery ore samples from the Bicholim deposit :

	Sample No. 1	Sample No. 2
Above 12 - mesh ...	14.12	19.56
Below 12-mesh above 20-mesh	10.87	11.00
,, 20 ,, ,, 45 ,,	9.88	7.64
,, 45 ,, ,, 60 ,,	10.15	9.43
,, 60 ,, ,, 80 ,,	8.97	9.60
,, 80 ,, ,, 120 ,,	15.60	10.34
,, 120 ,, ,, 170 ,,	11.74	8.72
,, 170 ,, ...	18.52	23.42
Total...	99.85	99.71

The above ore samples were also run through an Isodynamic magnetic seperator. The ratio of the non-magnetic or feebly magnetic to strongly magnetic fractions in the ore is approximately eight to one.

CHEMICAL NATURE

According to Krishnan (1955, p.103) the iron ores of Bicholim, excluding Sirigao mines, have the following composition :

	1	2
Fe ...	59.70	61-62
SiO_2 ...	1.35	1-2
P ...	0.056	0.045
S ...	0.052	traces
As ...	0.012	-
Mn ...	-	Max. 0.5
H_2O ...	-	6

TABLE I

Chemical composition of hard ore

Constituents	1	2	3
Fe_2O_3	87.26	84.71	90.17
FeO	0.26	0.70	1.16
SiO_2	0.80	0.64	0.72
Al_2O_3	1.88	4.75	1.79
TiO_2	-	-	-
CaO	0.14	0.95	0.62
MgO	0.11	0.21	0.21
MnO_2	Traces	Traces	Traces
P_2O_5	0.07	0.05	0.09
SO_3	Traces	Traces	0.045
CO_2	-	-	-
H_2O^+	9.30	7.58	5.02
H_2O^-	0.07	0.37	0.43

1 and 2, Sirigao-Bicholim deposit.

3. Sanquelim deposit.

TABLE II

Chemical Composition friable ore

Constituents	1	2	3
Fe_2O_3	89.85	91.98	91.10
FeO	0.66	1.04	2.22
SiO_2	0.90	0.68	2.42
Al_2O_3	1.56	0.20	0.15
TiO_2	-	-	-
CaO	0.91	0.44	0.43
MgO	0.26	0.18	0.19
MnO_2	Traces	Traces	Traces
P_2O_5	0.07	0.05	0.05
SO_3	0.03	0.01	0.006
CO_2	-	-	-
H_2O^+	5.62	5.10	3.37
H_2O^-	0.08	0.08	0.11

1 and 2. Sirigao-Bicholim deposit.

3. Sanquelim deposit.

TABLE III

Chemical composition of powdery ore

Constituents	1	2	3
Fe_2O_3	92.20	92.59	95.34
Fe_2O	2.71	4.33	1.23
SiO_2	1.84	1.62	0.70
Al_2O_3	0.94	0.24	0.30
TiO_2	-	-	-
CaO	0.35	0.59	0.38
MgO	0.19	0.11	0.14
MnO_2	0.11	-	Traces
P_2O_5	0.16	0.08	0.09
SO_3	0.01	Traces	0.008
CO_2	-	-	-
H_2O^+	1.29	0.43	1.73
H_2O^-	0.21	0.07	0.14

1 and 2. Sirigao-Bicholim deposit.

3. Sanquelim deposit.

Regarding the ores of Sirigao he wrote :

> The ore is similar to that of Bicholim and contain 57 to 58 per cent iron.

It may be pointed out here that the analysis, presented by Krishnan (1956), was not concerned specifically with the type of ore dealt herewith.

In order to determine whether there was any significant variation in the proportion of iron, silica, alumina, phosphorus, etc., in the main body of the ores, sets of two samples of hard, friable and powdery ores have been selected out of the collection from Sirigao-Bicholim deposit and one set from Sanquelim deposit. Care has been taken to take a particular set of samples from the same mine section. The samples were analysed by Geo-Chem Laboratories (P) Ltd., of Bombay. The results obtained from them are furnished in Table I, II and III.

Discussion

The analytical results reveal that there is a gradual decrease of certain chemical constiuents and corresponding increase of others from the upper to the lower parts of the ore body. Obviously, these facts not only signify the important changes in their chemical nature corresponding to the vertical distribution of the ores but also, to some extent the process which could have possibly been responsible for the differentiation of the original protore into hard, friable and powdery ores. The maximum and minimum values for the different constituents, given below, are averages of two samples from Sirigao-Bicholim deposits.

Iron Oxides.- Fe_2O_3 content reaches its minimum value in the hard and maximum in the powdery ore. This increase in the Fe_2O_3 content from the upper part to the lower part of the ore body also holds good for the Sanquelim deposit. On the other hand, the FeO content (0.5 °/o) is appreciably low in the hard ore and as high as 3.5 °/o in the powdery ore, the increase being about 7 times that of the hard ore. The FeO value in the friable ore is about 1.7 times that of the hard ore. It is, therefore, evident that alongwith Fe_2O_3 , FeO also increases from hard to powdery ore.

Silica.- An examination of the Bicholim ores shows that there is also a regular increase of silica from 0.72 °/o in the clean hard ore, through 0.89 °/o in the friable ore to about 1.73 °/o in the powdery ore. This shows an appreciable rise in silica of about 2.4 times from the hard to powdery ore.

Alumina.- Alumina is fairly low in all the ores. Unlike iron oxides and silica the average Al_2O_3 content decreases uniformly from 3.3 °/o in hard ore to 0.5 °/o in powdery ore.

Phosphorus.- P_2O_5 is very low in all the ores. It, however, does not show any significant variation in the different ores as the average value ranges between 0.06 °/o and 0.12 °/o.

Titania and Manganese.- Both of these two constituents are either absent or occur in traces in all the three types of ores. Titania is completely absent while manganese exist but in traces only.

Carbon Dioxide.- No CO_2 was detected in the ores, which obviously indicates the absence of any primary or secondary

carbonate mineral in the ores.

Lime and Magnesia.- Both lime and magnesia are considerably low and do not exceed even one per cent. On the average the CaO content in all the varieties of ore is 0.56 °/o whereas MgO is 0.17 °/o.

Sulphur.- SO_3 is almost insignificant and occurs in traces.

Combined Water.- The combined water shows a definite tendency to decrease from 8.44 °/o in hard ore, 5.36 °/o in friable ore, to 0.86 °/o in powdery ore.

MINERAL COMPOSITION

The mineral composition of the ores by weight per cent has been calculated from the results of chemical analyses aided by a first hand knowledge of their mineral composition. The hydroxides of iron is represented by limonite and the oxides by hematite and magnetite. The silica content in all the varieties of ore is abnormally low and does not bear any significant relation with the alumina. It is, therefore, presumed that silica occurs as a free constituent i.e., quartz, instead of forming any silicate mineral of alumina. If this be the case then there is a possibility of existence of alumina in the ore as common alumina hydroxides. However, due to its negligible occurrence in the ore no further discussion is necessary here. Almost all of H_2O^+ entered into Fe_2O_3 to form limonite ($2Fe_2O_3 \cdot 3H_2O$). Similarly, all the FeO also combined with the required amounts of Fe_2O_3 to form magnetite ($FeO.Fe_2O_3$). Rest of Fe_2O_3 formed hematite (Fe_2O_3).

The average composition of two samples (Table I, II and III, Column 1 and 2.) of various types of ore and their corresponding mineral composition by weight in per cent is given below :

Average Hard Ore

SiO_2	=	0.72 °/o	Quartz	=	0.72 °/o
Fe_2O_3	=	85.74 ,,	Hematite	=	34.40 ,,
FeO	=	0.48 ,,	Magnetite	=	1.54 ,,
H_2O^+	=	8.44 ,,	Limonite	=	58.47 ,,
Al_2O_3	=	3.31 ,,	Accessary minerals	=	4.87 °/o

Average Friable Ore

SiO_2	=	0.89 °/o	Quartz	=	0.89 °/o
Fe_2O_3	=	90.91 ,,	Hematite	=	57.55 ,,
FeO	=	0.85 ,,	Magnetite	=	2.74 ,,
H_2O^+	=	5.36 ,,	Limonite	=	36.77 ,,
Al_2O_3	=	0.88 ,,	Accessary minerals	=	2.05 °/o

Average Powdery Ore

SiO_2	=	1.73 °/o	Quartz	=	1.73 °/o
Fe_2O_3	=	92.39 ,,	Hematite	=	84.02 ,,
FeO	=	3.52 ,,	Magnetite	=	11.34 ,,
H_2O^+	=	0.86 ,,	Limonite	=	0.59 ,,
Al_2O_3	=	0.59 ,,	Accessary minerals	=	2.32

CLASSIFICATION

In an attempt to classify the iron ores, Gross (1959, p.87) stated

> one of the difficulties in the classification of ore deposits is to establish a system that will account for some of the diverse interest of the exploration geologist, the mining engineer and the metallurgist or mineral economist.

Ghosh et al. (1963) classified the iron ores of Bihar, Orissa and Madhya Pradesh on their physical characters. Nandy and Dutta (1963, p.20, Table I) also proposed a physical classification for the iron ores of Bihar and Orissa although in their classification they also considered the mineralogy.

Sikka (1963) made an attempt to classify some of the Indian iron ore deposits of Bihar, Orissa and Madhya Pradesh more or less on lines similar to that as proposed by James (1954), who classified the iron ore formations of Lake Superior on the basis of their lithology and facies. In addition, Sikka also noted in various open pit iron mines yellow, brown, red and blue ores which, according to him, also indicated stratigraphic sequence and definite mineralogical and chemical boundaries. Nandy and Dutta (1963), however, strongly objected to Sikka's views as they failed to recognise any colour scheme for stratigraphy of the iron ore deposits of Bihar and Orissa.

From his own experience and observation the present author was, however, unable to recognise any lithological unit other than the banded magnetite-hematite quartzite belonging to the oxide facies of James (1955). Moreover, the iron ores do not show any detectable variation in colour. It is, therefore,

TABLE IV

Classification of the iron ores of Bicholim and Sanquelim , Goa.

Nature of ore	Physical properties	Average mineral composition wt. %	Chemical constituents wt. %
Hard	Hard, compact and thinly laminated. Lesser tendency to break along bedding laminations. Steel grey to brownish grey in colour. Sp.gr. 3.0-3.3.	Hematite: 34.40 Magnetite: 1.54 Goethite: 58.47	Fe: 59.0-64.0 SiO_2: 0.5-1.0 Al: 1.0-2.0
Friable	Soft, usually porous, thinly laminated having a greater tendency to break into thin slices parallel to bedding laminations. Appears biscuity when highly jointed. Sp.gr. 2.7-3.0.	Hematite: 57.55 Magnetite: 2.74 Goethite: 36.77	Fe: 62.0-64.0 SiO_2: 1.0-1.5 Al: 0.1-0.8
Powdery	Loose and finely granular. Grain size range: 80 % below 20-mesh. Dark grey to bluish grey colour. Sp.gr. 3.2-3.5	Hematite: 84.00 Magnetite: 11.34 Goethite: 0.59	Fe: 65.0-67.0 SiO_2: 1.0-2.0 Al: 0.1-0.5
Lateritized	Usually hard and massive. Occasionally porous and laminated. Inclusions of clay materials are frequent. Dark reddish-brown to chocolate brown colour. Sp.gr. 2.8-3.5.	Not determined	Fe: 40.0-55.0

evident that neither the lithology nor the colour could be of any use to classify the iron ores of Bicholim and Sanquelim.

However, it is true that for practical reasons a classification based on physical characters of the ores has certain advantage over any other features depending on colour, lithology, facies , mineralogy, chemical composition, etc., since it makes easier to distinguish the ores through visual examination. Due to simplicity of identification at first sight, the classification may also be acceptable to persons concerned with iron mining industry.

Such a physical classification, however, may not suit the economic geologists as well as metallurgists because, their prime consideration is to know the chemical and mineralogical composition of the ores rather than their physical characters. In the Table IV an attempt has been made to classify the iron ores by which whether a field geologist, mining engineer or a mineral economist can be benefitted in their respective fields of interest.

ECONOMIC OUTLOOK

Status of Indian Iron Ores

India is endowed with enormous reserves of high grade iron ores which can meet the growing demand of iron and steel industry of the country as well as sustain her export trade for several decades to come. Hematite is the chief commercial source of iron ore in India and it is being largely raised from the states of Bihar, Orissa, Madhya Pradesh, Andhra Pradesh, Mysore and also to some extent from Goa. Prior to independence there were only two

small iron and steel plants in the country, the annual production of which was about 2 million tons.

Vitality of India's economy depends significantly upon her iron and steel industry which is being given a high priority in the post-independence planning and industrial development programme. After independence of the country in 1947, India's mineral resources planners have embarked upon a scheme to promote export trade in iron ores as well as to increase production of iron and steel in the country through proper development of some new deposits and installation of four new iron and steel plants within or close to several iron producing states. In the fourth five year plan, they have set a steel target of about 16 million tons to be produced annually by the present six plants using about 25 million tons of high grade ores and another target of raising 25 million tons of ore for export. The progress with respect to both has been very slow and rather disappointing because the steel production has barely touched 9 million tons and the total ore output did not exceed 24 million tons till by the end of 1969. There are various reasons for this failure of which, foreign exchange difficulty, delayed foreign aid to complete and expand some plants, internal economic instability and unexpected rise in the production cost, slow mechanisation of the mines, increasing inland transportation cost and limited handling facilities of ores at the Indian ports are worth mentioning.

Reserves and Present Position

According to the last available report of the Indian Bureau

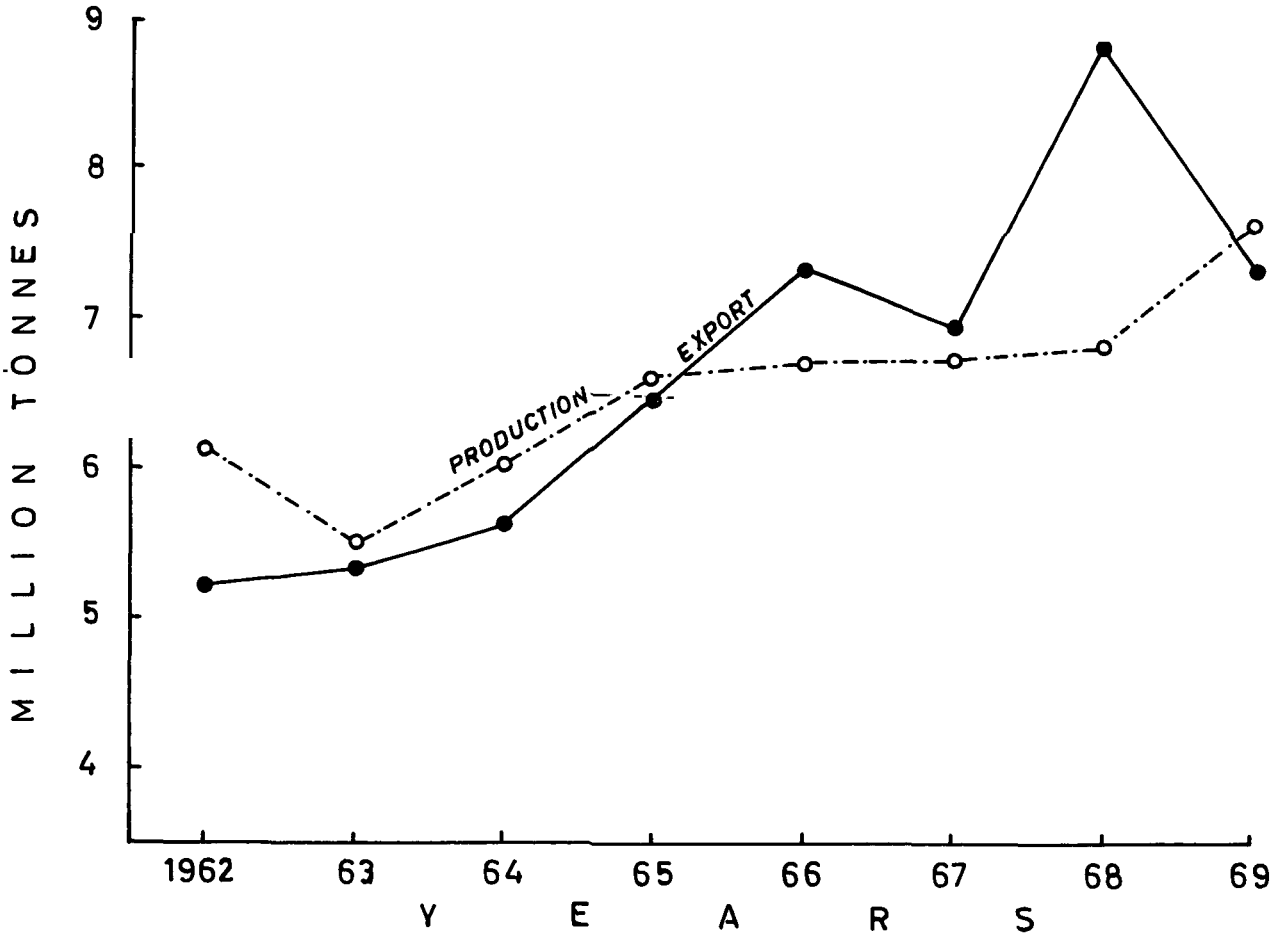


FIG. 4 TOTAL PRODUCTION & EXPORT OF IRON ORES FROM GOA - DURING 1962 TO 1969

of Mines (1963) the total amount of proved and indicated reserves of high grade hematite ores in India is about 5,401 million tonnes, of which Goa shares about 525 million tonnes with a grade ranging from 57 to 62 °/o Fe. A more recent estimation of iron ores reserves in the territory of Goa, made by the Geological Survey of India, is about 405 million tonnes of which, about 94 million tonnes of ores are hard with 58 °/o Fe and 311 million tonnes are friable and powdery ores with 62 °/o Fe. From the above data it is evident that the average ratio of hard to friable-cum-powdery ore of the territory will be as near 1 : 3. It may be pointed out that the hard ores of the Goa mines are now fast getting depleted. Out of the total iron ore reserves, about 75 °/o comes from northern Goa, 19 °/o from the Central Goa and about 6 °/o from South Goa. Fig. 4 shows that the annual production of iron ores of Goa from 1962 to 1969 has gradually been increasing and this trend is likely to continue in future.

As regards the reserves of Sirigao-Bicholim and Sanquelim deposits of north Goa, it is true that the data published so far are not very reliable. Fermor (see Krishnan, 1955) estimated that hard ore within a depth of 50 feet was about 3 million tons per mile of the Bicholim deposit measured lengthwise. Based on an estimation supplied by the local mine owners, the U.S.A. Bureau of Mines in its Mineral Trade Note (1952) puts 250 million tons of iron ore for Bicholim deposit (see Krishnan, 1955, p.104). This estimation of the so called Bicholim deposit appears to be exclusive of the Sirigao deposit, which is considered here as a part of the

Bicholim deposit. Krishnan (1955), however, stated that the claimed reserves of Sirigao deposit were about 30 million tons. Following are the more reliable estimations of iron ore reserves of Sirigao-Bicholim and Sanquelim depositavilable from an unpublished report of the Geological Survey of India (1963) :

	Approximate reserves in million tons		
	Hard (lumpy) ore	Friable and Powdery ore	Total
Sirigao-Bicholim	21.41	65.67	87.08
Sanquelim	3.01	7.28	10.29
Total	24.42	72.95	97.37

At present all the important iron ore mines of Goa are free or merchant mines which subsist entirely on the foreign market. The economy of Goa today depends much on the mining and export trade of iron ores. More than 30,000 people of different skills are now engaged in this mining industry, which is a concern of about 400 big and small owners of mines. Japanese interest is the backbone of Goa's iron ore mining industry. Other big foreign customers are West Germany, Italy, Czechoslovakia,etc.. Among the several important iron ore producing states of India, Goa is the only maritime state which has the unique advantage of shipping her iron ores conveniently to foreign markets at competitive rates.

Although the iron ores of Goa are physically and chemically variable, obviously for the reason that these are replacement

deposits and comparatively not of very high grade with iron ranging between 55 to 62 °/o, yet they have been able to capture a secure position in the international market because of their cheap f.o.b. Rich deposits of iron ore of North Goa are ideally situated within a distance of 10 km or nearly so from the nearest navigable portion of the river Mandovi which connects the Marmugao port on the Arabian sea. Proximity of the port from the mines and excellent inland waterways are the main factors that have made the f.o.b. of iron ores cheaper.

Quality-Control

According to the Indian Bureau of mines (1963) the general specification of the Indian iron ores, suitable for the country's blast furnaces are as follows :

Fe	:	57 to 63 °/o
SiO_2	:	2 to 6 °/o
Al_2O_3	:	5 to 6 °/o
P	:	0.03 to 0.15 °/o
S	:	below 0.02 °/o

Maximum ratio of

SiO_2 : Al_2O_3 = 1 : 1.5

Combined SiO_2+Al_2O_3 = 10 °/o max.

Since the bulk of iron ores of Bicholim falls within a close range of the above specification, they are suitable for feeding the country's blast furnaces apart from their having higher export values.

But a strict quality control of such a variable type of ore as of Bicholim is specially desired because the quality of iron

ore used in the blast furnaces greatly influences the quality of the final product in the modern steel industry. Moreover, the cost of the raw material is much dependent on the consistency of specifications in the highly competitive internal as well as foreign trading.

According to some authorites, increase in gangue in iron ores by about 1 °/o increases the coke rate by 25-30 kg , flux by 30 kg , and slag by 40 kg for every tonne of metal produced. This also involves a production loss of about 4 °/o.

Therefore, the quality of these ores should necessarily be controlled right from the mine site. For the effective quality control of the iron ores in question, an early implementation of the following measures is suggested :

1) A general assessment of the physical and chemical variation of the ores is necessary before mining the deposit.
2) To minimise the range of predicted iron, the bore hole intervals should be closer than at present.
3) To determine the type and quality of the ore with reasonable accuracy, samples should be drawn at regular intervals from the available bore holes, blast holes and mine faces for physical and chemical examinations.
4) Adequate mechanical facilities should be provided for a quick handling and screening of the powdery ore as well as the lumpy ore round the year.

5) There should be a regular check on the desired quality and specifications of the ores from the mine head to the loading station.

6) Further practice to blend the ores should be stopped and the powdery ores and ore fines should not be dumped together.

7) Greater attention should be paid to save the large wastage of the powdery ore, particularly during the rainy season, through quick shovelling and distribution.

Future Prospect

As the lumpy ore of Goa is nearing exhaustion, it is now left with large quantities of powdery ore which, as it is, may face difficulty to cope with the day-to-day growing competition in the world market, obviously because the ore powders cannot be fed directly to the blast furnaces. The only solution for the promotion of export trade, therefore, lies in agglomerating the powdery ore into pellets since they are now widely recognised as a better feed for the blast furnaces than the sinter or any form of ore. Visualising fast depletion of lumpy ores at Bicholim and other iron ore localities, in Goa, added with the recent trend to apply beneficiation techniques in the iron industry of our country, the Chowgule and Co., of Goa have recently put into operation a pelletising plant at their Pale mines with the active support of the Government of India. This happens to be the first Indian as well as Asian agglomeration plant to utilise the ore fines and powders and

thus, it is the first step to conserve the iron ore resources of Goa.

The commissioning of this agglomeration plant has increased substantially the demand of Chowgule's iron ores for the pellets produced from it ensure not only smooth blast furnace operation but also lower coke consumption and better yield. However, pelletisation of the blue dust has one disadvantage that the feed must have a high percentage of fine concentration in the range of at least 70 °/o - 325 mesh. This obviously necessitates very fine grinding of all the fractions of the blue dust consisting of 82 °/o of 20 - 170 mesh particles, and this happens to be the costliest phase of a concentrating flow scheme.

To help boost up iron mining industry and also to procure profitable foreign trade, the Government of India has allocated to Goa a foreign exchange of about rupees 27 million. With this substantial aid the mining industry expects to reach the proposed annual target of exporting 10 million tons of ore in near future. But, with the growing stringent specifications for the shipping grade of ore in the international market, Goa would not be able to get over her present difficulty of exporting the powdery ore unless serious efforts are being made to install at least one more pelletising plant and establish an iron and steel industry in the territory.

Very recently, the Government of India has announced through a notification that allocation of a public sector steel plant to

Goa in the fifth five-year plan is being actively considered. Obviously, such a step is most welcome as it would greatly assist Goa to build up her economy through the production of iron and steel and the steady supply of a part of the product to some of the foreign buyers in future. However, the State support for the promotion of export trade in iron ores as well as pellets should continue even after a new iron and steel plant is erected in Goa because several foreign countries are now keenly interested to have a long-term contract to import Goa's iron ores. For this, it is all the more necessary to allocate to Goa another agglomeration plant preferably nearer to the Bicholim town or at Piligao. This plant together with the present one, would ensure not only steady supply of pellets to the internal as well as external markets, but also optimum production at minimum cost in future.

The foregoing review of the facts and figures of Goa's iron ore resources provides enough justification to the author's belief that with a planned mining, beneficiation and metallurgy of the iron ores and their export promotion, Goa can well become an ideal state in the country to utilise its potential deposits of iron ores for industrial development and economic progress.

Chapter V

STRUCTURE OF THE ORE DEPOSITS

GENERAL STATEMENT

The close association of the iron ore deposits with the banded ferruginous quartzite in Bicholim and Sanquelim warrants study of their structure as one unit instead of dealing them here separately. Hence, the structure of banded ferruginous quartzite, which is the protore in this case, has been described interchangeably with the ore deposits.

Due to their greater resistance to weathering and erosion, these ferruginous quartzites generally form conspicuous ridges which extend over a considerable distance in the area. Among them, Sirigao-Bicholim ridge is by far the longest and extends for about seven kilometers. The other two, viz., the Redeval and Sanquelim ridges are comparatively shorter and extend for about 1.75 and 2.5 km respectively. Remarkably, the strike of all these ridges is from NW to SE, excepting a few local departures from this direction.

Extensive lateritization has hardly left any fresh outcrop of the iron deposit or banded ferruginous quartzites in the area under review. On the contrary, the laterites have greatly obscured most of their structural features on the outcrops. To a large measure the data, which were collected from the various open cast mine sections, were found to be most useful for this study. It is, therefore, obvious that under such field conditions all other data collected from outside the mines were comparatively less important. The author, however, made use of all available data from the mine

sections, bore holes and also from the scanty natural exposures of the formations. Perhaps a more comprehensive account of the structural features of ore deposits could have been presented if the area had no such limitation of their exposures.

The structures of the Sirigao-Bicholim and the Sanquelim deposits have been described separately. A portion of the Sirigao-Bicholim deposit, falling within the property of Chowgule and Co., at Sirigao, was mapped in detail by means of a plane table because it was found to be a key area for structural study of the deposit.

STRUCTURAL FEATURES

For descriptive purpose, the deposits were broadly divided into two sectors viz., 1) northwestern sector consisting of Sirigao-Bicholim and Redeval deposits and 2) southeastern sector consisting of Sanquelim deposit.

Northwestern Sector

Again, in the northwestern sector, there are two separate deposits of iron ores occurring in the country rock, phyllites (Fig.5). The two deposits have a general NW-SE strike. The longer one is the Sirigao-Bicholim deposit which extends from Sirigao to Bicholim and the smaller one, known as Redeval deposit, occurs about 400 m northeast of the former.

Sirigao-Bicholim Deposit.- A first hand knowledge of the structure of Sirigao-Bicholim deposit can be gathered from the topography of the ridge of ferruginous quartzites which extends from Bicholim-Piligao road on the southeast to Sirigao on the northwest. Between its southeastern end and Sirigao hill in the northwest, the ridge runs almost straight for a distance of about 4.5 km and gains height northwestward. At Sirigao hill the ridge suddenly takes an acute turn southwards and continues in that direction for about a km or nearly so. Near the boundary between Chowgule and Bandekar mining concessions, the ridge again turns to its original northwest direction. The ridge gradually converges and ultimately disappears west of Sirigao village, which is about 1.5 km from its last bend. The topography of this ridge has largely been controlled by the major structural features of the ore deposit as would be described hereafter.

The structure of the iron ore deposits at Sirigao mines affords a very interesting problem for field study and mapping. For this purpose the Sirigao mine section was mapped carefully by a plane table on a scale 1 : 2,400. Additional informations, obtained from the bore holes particularly, in those places where mines have not been opened, were of much help to complete the structural map of the mine section which ultimately proved to be a key area.

The Sirigao mines have been developed from the northern and southern slopes of the quartzite ridge between survey stations B and M (Fig.6). Rest of the concessions remain to be worked out.

Locally, the northern and southern workings are known as Coplegaichem and Goigonem concessions respectively.

The northern ore body in Coplegaichem concessions has been exposed well through continuous and systematic mining between survey stations B and I. On the eastern part of the concessions, ores are generally hard and laminated whereas friable and soft ores predominate on its western part. Therefore, better structural details of this ore body were available from these concessions than elsewhere in the mines. Again, in the northern deposits, between the survey stations C and F i.e., on 30M, 35M, 40M and 45M levels, the workings were more developed than on 50M, 60M and 65M levels. The general strike of the ore body recorded in this well-developed mine section is about N 40°W to N 50°W. The amount of dip, however, varies greatly ranging from 35° to 50° northeast. The attitudes of the joints, which were recorded from the faces of 30M, 35M and 45M levels, are mostly oblique and either vertical or steeply dipping at 80° to 85° SE. Minor folds are more conspicuous in the foot wall clays and ochreous country rock than in the main body of the deposit. The axial trend of these minor folds is more or less the same as that of the general strike direction of the deposit. On account of their small dimension it was not possible to show them on the map. The maximum thickness of the deposit recorded here is about 36 m , but it may not be the true thickness because of the presence of a number of minor folds in the ores. At 20M level, a vertical fault of some significance crosses the ore body

obliquely in the direction N 35° E. Lateritic materials occurring as fault gouge give the appearance of a dyke along the fault plane. The fault has not much affected the alignment of the ore body.

The ores quarried at the lower 15M level on the western part of the mine are soft and friable. They grade into ferruginous laterite towards the hanging wall side and into powdery ore towards the foot wall. Their strike in this part is about N 35°W and dip, 30° to 50° northeast. Minor folds and faults are conspicuously exposed in the undisturbed face of 15M level where powdery ore predominates.

Further westwards, beyond the survey station B, the ore body disappears below a laterite capping. However, its underground continuity in this unexposed portion, particularly, west of the survey station A, has been proved by the data obtained from the bore hole Nos. 246, 247, 252 and 264 (Fig.7).

Unlike in the Coplegaichem concessions, where a thick and continuous ore band was encountered, in the Goigonem concessions, there are several minor ore bands with intervening clay and ochreous bands which could be seen between survey stations K and N and particularly, in 50M and 58M level workings, now lying almost in an abandoned state. In the bench faces, these alternate thin bands of ore and country rock are somewhat well-defined. The bands generally strike NW to SE but their amount of dip are variable as could be seen at the ore bands I, II, III, etc.. For example, the strike and dip of band I is N 47°W and 53°NE

and those of band II is N 40°W and 48°NE. Likewise, the width of the bands are also variable and they are as follows :

Band	width
I	12 meters
II	20 ,,
III	10 ,,
IV	8 ,,
V	11 ,,

A close examination of these ore bands indicates that they are the traces of subsidiary anticlines and synclines truncated by mining operation and that their axes trend NW-SE. Widespread mining at Goigonem workings has left a few synclinal troughs from which the ores are being mined leaving the intervening anticlinal portions composed of foot wall rocks. Since there is no mining activity in the area lying between survey stations N and T, no surface indication regarding the continuity of these ore bands westwards was available. However, several bore holes (nos.54A, 158, 159, 206, 222, 224, 227, 236 and 239) in this area proved the existence of a number of ore bands at various depths. A careful study of these bore hole data indicates that the number and position of the concealed ore bands fairly agree with those encountered on the surface. Therefore, on the basis of the above data the continuity of some of the ore bands ,encountered at 50M and 58M levels further westwards below the surface could fairly

be ascertained. It is, however, obvious that their thickness may not remain uniform over a considerable distance. Further, it may be deduced from the bore holes (nos. 242, 245, 253 and 263) that these small ore bands gradually converge north-westwards with diminishing width of the intervening phyllites until they coalesce into a single wide band somewhere below the survey station T. The strike of the country rock recorded here is about N 40°W. The amount and direction of the dip are about 55°NE. Further westwards, beyond the survey station T, a small portion of the ore body is exposed on the side of a road leading to the Chowgule's mine office. The strike of this exposed part of the ore body is about N 42°W while the dip is either vertical or about 80°NE.

Thus, it is evident that there are distinctly two separate parts of the ore band with an intervening tract of phyllites. The band occurring at Coplegaichem and the other at Goigonem concessions, are the productive workings of Sirigao mines. Since the dip and strike of these two ore bands are more or less the same and they converge northwestwards, the structure indicated is an isoclinal anticline plunging northwestwards.

The intervening portion of the two ore bands at Sirigao mines consists of weathered phyllites mixed with clay and ochre, the presence of which below the surface was also confirmed from some bore hole data of this part (nos. 160, 161). However, the bore hole no.160 recorded three thin ore bands with intervening phyllites at depths of 9.2 m, 12.2 m and 14.2 m. These ore bands

in all probability correspond to some of the individual thin iron ores exposed at the Goigonem concessions.

Therefore, analysing the structural data as stated above, it is evident that the iron ore bands of Coplegaichem and Goigonem concessions correspond respectively to the northern and southern limbs of the Sirigao plunging anticline, which was folded isoclinally and overturned southwestwards. Its plunge is 20° northwestwards. At the western extremity of the deposit i.e., west of the survey station A, where the two ore bands converge and ultimately disappear, the anticline closes on itself indicating its nose. Accordingly, the two ore bands may be regarded as belonging to one and the same ore body folded into an isoclinal anticline plunging N 40°W. The axis of the anticline would then pass somewhere through the middle of the phyllites included between the two ore bands. The crestal region of the anticline has largely been eroded and as a result of which the anticlinal limbs appear as two different bands seperated by the foot wall phyllites. Among these two ore bands, the southern one at Goigonem mines is more instensely folded than the northern one. The intensity of folding was judged by the presence of a number of minor folds which appear on the surface as several subparallel ore bands.

A cross-section along the line AB illustrates structure of the Sirigao deposit.

At the eastern extremity of the Coplegaichem concession, between the survey station G and 80M level, the strike of the

northern ore body of Sirigao mines gradually changes from N 65°W to about E-W within a distance of about 230 m. The amount of dip at 60M level is about 40°N. Further north, at Bandakar's mining concession, existence of the ore body has been proved from a number of small quarries (Fig.5). The strike recorded in the quarry sections is about N 30°W with northwesterly dips amounting from 40° to 52°. Owing to unsystematic mining or no mining operation in a major portion of this concession , further structural details were not readily available from the deposit. However, it is conclusive that the two deposits, one in Bandakar's property and the other at Coplegaichem concessions of Sirigao mines, though seperated by a valley, converge towards each other at the concessions boundary of Chowgule and Bandakar. The structure of this part of sharply bent ore body having opposing dips, is that of a syncline plunging NNW. Its axial trend is NNW-SSE, which makes an angle of about 15° north of the axial trend of the Sirigao anticline.

Beyond the Bandakar's mining concession, further northwards and northeastwards there are several small pits and quarries of Dempo and Co., from which ore body was found to be continuous and to change its strike gradually to N 40°W, east of Sirigao hill (161.34 m). In this part, changes in strike and dip are : N 20°W, N 10°W, N 48°E and N 70°W corresponding to the dips 38°SW, 34°SW, 30°NW and 70°NE. Such conspicuous changes in strike and dip in this section of the deposit are attributed to an

anticline corresponding to the syncline on its south, described earlier. The axis of this anticline is parallel to that of the adjacent syncline.

From the foregoing structural description it may be seen that the ore body is bent in the form of an 'S' between the survey station A in Sirigao mines and east of Sirigao hill. This 'S'-shaped outcrop pattern of the deposit is due to the presence of a drag fold affecting the isoclinal anticline which was encountered at Sirigao mines.

The portion of the deposit between east of Sirigao hill and south of the Bicholim township are mostly well-exposed as a result of almost continuous mining operation all along this belt. The general directions of strike and dip of this part of the deposit remain unchanged excepting some local variations. The amount of dip, however, varies greatly. For example at 4-Top workings, strike of the ore body is about N 40°W whereas the amount of dip varies from 45° to 60° NE. The joints noted in the mine faces are mostly oblique and their attitude is either vertical or dipping about 80°SE. At a lower level in the same workings where mostly powdery ores are exposed, there are some minor folds and faults.

Similarly, about a kilometer southeast of Lamgao, at 2-Top workings and further eastwards, the ore body gradually thins out and ultimately disappears near the Bicholim-Piligao road. The strike of the ore body in this part is about N 45°W. Amount of dip varies between 40° and 50°NE.

Redeval deposit.- The Redeval deposit forms a seperate outcrop about 400 m northeast of the Sirigao-Bicholim deposit and runs almost parallel to the latter for about 1.75 km along a quartzite ridge. The intervening tract consists of phyllites which are covered by laterites sloping northwards. Both northwestwards and southeastwards, the ridge gradually loses its height and width till it merges in the country rock at lower levels.

The Redeval deposit is being worked out on almost all along the northern slope of the ridge. The northwestern and south-eastern parts of the workings are locally known as 4-Bottom and 3-Bottom workings respectively. The workings are confined to hard and laminated ore zone close to the surface. Structurally, the deposit seems to be rather simple since there is practically no change in strike and dip along the entire length of the deposit. At 4-Bottom workings, the ore body shows about N 45°W strike and northeasterly dips ranging from 50° to 55°. The deposit extends continuously along its strike direction from 4-Bottom to 3-Bottom workings. The strike and dip of the ore body at 3-Bottom workings are about N 40°W and 48° to 65° NE respectively.

The above structural features suggest that the lenticular Redeval deposit has a general NW-SE strike and northeasterly dip. Its structural relation with the adjacent Sirigao-Bicholim deposit has so far been controversial as could be judged from the following account :

Krishnan (1955, p.103) mentioned this lenticular deposit of iron ore as the northeastern limb of an isoclinal syncline. Obviously, then the other limb of the syncline would correspond to that part of the Sirigao-Bicholim deposit which occurs on its southwest i.e., between Sirigao hill and south of Bicholim township.

According to Gokul (1963), this smaller outcrop of iron ore is the repetition of the Sirigao-Bicholim deposit due to a strike fault which extends northwestwards from Lamgao.

It may be pointed out here that Gokul (1963) has not shown any field evidence in support of his statement. In the absence of any positive field evidence, it would rather be difficult to entertain the above suggestion. Further, the question as to why the strike fault is restricted to this part only instead of extending further westward and displacing at least a part of the 'S'-shaped deposit on its northeastern side creates some doubt in this case.

In the light of above argument added with the nature of the deposit which converges northwestwards and slightly diverges southeastwards, and absence of any distinct fault valley in the intervening country rock, the present worker considers the Redeval outcrop to be a case of repetition due to truncation by erosion of the Sirigao-Bicholim anticline in this part.

A cross-section along the line CD shows structural relation between the Sirigao-Bicholim and Redeval deposit with associated country rock in between (FIG. 5).

An overall picture of the Sirigao-Bicholim and Redeval deposit, the structure of which have so far been described in parts is summarised as follows :

It is fairly well-established that the part of the Sirigao-Bicholim deposit forms an isoclinally folded anticline with its axis trending NW-SE. The same anticline was also found to be continuing southeastwards with the same general trend of its axis. The southwestern limb of the anticline, between Sirigao hill and Bicholim-Piligao road, is wider and also larger than its north-eastern limb represented by the Redeval deposit. The 'S'-shaped bend of the anticline between the Sirigao hill and Sirigao mines represents a drag fold due to which the main anticline was refolded and dragged further southwest of Sirigao.

Southeastern Sector

There is only one major deposit of iron ore in the south-eastern sector of the area. It is locally known as Sanquelim deposit.

Sanquelim Deposit.- The Sanquelim deposit crops out on a quartzite ridge which extends over a distance of about 2.5 km from west of Valvota river to the village, Gauntana and follows the general NW-SE strike of the country rocks (Fig.5). From Sanquelim hill (97.03 m) the ridge gradually diminishes in width and relief northwestwards and finally merges into the laterite, west of the Valvota river. The deposit is being worked out both

from the northern and southern slopes of this ridge.

In the middle of the southern workings, the ores are represented by all the three known varieties which are well - exposed due to extensive mining activity. The strike of the ore body is about N 40°W. Amount and direction of the dips are not uniform in a sense that besides the dominant northeasterly dip amounting to about 60° - 70°, there are a few steep southwesterly or almost vertical dips. These variation of dips are, however, local and due to a series of minor folds in the ore body.

Further westwards, where the deposit becomes narrow, there are still a number of quarries in which the strike of the ore body is about N 45°W, whereas the amount of dip varies from 70° to 75° SW.

As compared to the working on the southern slope, the major portion of the northern slope of the Sanquelim deposit has not yet been worked out except at a few places viz., northeast of Sanquelim hill and east of Valvota river. The strike of the ore body northeast of Sanquelim hill is about N 43°W with the amount of dip varying from 56° to 65° NE. The same northern deposit was again exposed, east of Valvota river, in several abandoned quarries. The strike and dip for this part of ore body are about N 46°W and 54°NE respectively.

The deposit bifurcates into two narrow strips on its southeastern side between Sanquelim hill and Gauntana. A narrow band of lateritized phyllites occurs between the two strips.

Although the amount and direction of dips in this part are locally variable yet the general northeasterly dip is maintained and the strike continues to be NW-SE.

Considering seperately the structural elements of the northern and southern ore bands of the Sanquelim mines, it is evident that both the ore bands converge northwestwards and finally they join up and constitute one deposit. Thus, between the river Valvota and Gauntana, the deposit forms an elongated 'V'-shaped outcrop which obviously represents an eroded anticline, the axial trend of which is almost NW-SE and plunge about 30°NW. The dip readings of the limbs of the anticline suggest that this anticline is also isoclinal and somewhat overturned.

The nose of this anticline is located about 1.5 km northwest of Sanquelim hill while its two limbs correspond to the two different outcrops between Gauntana and Maulingiem. Obviously, due to erosion of the crest of the anticline on its southeastern side a narrow patch of foot wall phyllites was exposed and divided the deposit into two parts.

A cross-section along the line EF illustrates structure of the Sanquelim deposit (FIG.5).

STRUCTURAL CONTROL ON RESIDUAL IRON ORES

It has been widely accepted that two distinct relations may exist between the ore deposits and folds. A syngenetic or primary ore is older than folding while the epigenetic or

secondary ores are introduced after the folding (see Newhouse 1942, p.39). In other words, mineral deposits of syngenetic origin would obviously be subjected to the same tectonic influence as the enclosing rock and epigenetic deposits will mostly be guided by the rock structure (see Fermor, 1924).

According to the author's view, which will appear later in the text, the iron ore deposits of Bicholim and Sanquelim were originally syngenetic and subsequently, they were subjected to processes of residual concentration and enrichment. It is, therefore, expected that both the primary and secondary structures of the iron formations played their respective roles in controlling the localization of the iron ore deposits. It is also evident that the secondary ores were all derived from the protore ,banded ferruginous quartzite after their deposition, folding and subsequent alteration. Such structural features as bedding lamination, steeply dipping limbs of the isoclinal folds, etc., were basically responsible for localizing secondary ores since they make easy opening and channelway in host rock through which mineralizing solution may readily move (see Sullivan, 1957).

Narayanaswami (1959, p.96-97) pointed out that some of the Indian Precambrian terrains of intense deformation marked by en echelon folds and drag folds along the limbs of the major folds may be acknowledged as the structures favourable for localization of secondary iron and manganese ores. For example, the supergene iron ore deposits of Naomundi, Bonai, Keonjhar of Bihar and Orissa ; Bailadila iron ore deposits of Madhya Pradesh;

metasedimentary iron ores of Mysore and the manganese ore deposits of the Sausar series of Madhya Pradesh as well as those of Panch Mahals, Jhabua, Tirodi, etc., are all localized in synclinal troughs or anticlinal crests of en echelon folds.

Another noteworthy fact in the area under study, is that there is generally a great residual concentration of iron ores in the deeply truncated portions of the anticlines than those portions where the anticlines suffered limited erosion. In such deeply truncated anticlines, larger surface area of their limbs is exposed to meteoric water to percolate easily through the highly dipping bedding planes of the quartzites. A plausible explanation for the mode of concentration of ores in the limbs of truncated anticlines has been given by Adams (1911, p.168) while describing the origin and secondary concentration of the Cuynna iron ores of Lake Superior. Finding a more or less similar relation of the iron ore deposits of Bicholim and Sanquelim to their structures, the author finds logical justification to accept the idea of Adam (1911) which can be expressed better through quoting him as follows :

> The circulating waters entered the iron formation where the truncated lenses were exposed on the limbs of the anticline folds and tended to concentrate in the natural channels thus formed. At one time the actual rock surface was exposed and the level of the ground water stood some distance below the surface, and the meteoric waters entering the exposed surface worked downwards till the level of the ground water was reached. These downward circulating waters, heavily charged with oxygen, were responsible for the chemical reactions in the alteration of the iron formation.

If the above view is acceptable it can also explain for practically no residual concentration of iron ore in the untruncated part of the Sanquelim anticline.

Therefore, from the above consideration it may now be concluded that both the primary and secondary structural features of the iron ore formations have not only greatly controlled the distribution but also the concentration and enrichment of the iron ores of the area.

Chapter VI

MINERAGRAPHIC STUDY OF THE IRON AND ASSOCIATED MANGANESE ORES

GENERAL STATEMENT

So far no mineragraphic study of the iron ores as well as the associated manganese ores of Bicholim and Sanquelim have been made by any one of the earlier workers. The author (1965) had earlier studied the mineralogy of the iron and manganese ores of the Sanguem district of South Goa. Fermor (1909), however, gave a very brief account of the lateritic manganese ores of Goa but so far as the iron ores are concerned, no such account is available to date. In course of the present investigation the author, therefore, availed of the first opportunity to examine in detail the iron and the associated lateritic manganese ores of Bicholim and Sanquelim in north Goa.

The workable deposits of iron ores of Bicholim and Sanquelim occur along well-defined zones. Small and scattered pockets of lateritic manganese ores occur rather infrequently in these deposits particularly, in the hard laminated iron ores.

As far as possible all the available types of iron ore samples representing lateritic, hard laminated and friable were collected systematically from the different sections of open cast mines of Bicholim and Sanquelim. Some difficulty were encountered in preparing the polished blocks of some soft and friable specimens, which required continuous cooking in canada balsam before they were finally polished. The powdery ore was mounted on bakelite

block for this study. About 60 representative samples of iron ores including a few manganese ores from the area have been finally selected for ore-microscopic study.

Through mineragraphic study an attempt was made to identify the ore minerals and their assemblages, state of oxidation, and finally, their textural relations and paragenetic sequence.

MINERALOGICAL DESCRIPTION

The mineralogical description of various iron and manganese minerals, which are identified in polished sections under reflected light, are given below along with their characteristic physical characters. Chemical formulae of the iron and manganese minerals are adopted after Deer, Howie and Zussman (1962), and Hewett and Fleischer (1960) respectively.

Iron Ores

Hematite (Fe_2O_3).- The name hematite was first proposed by Theophrastus in 315 B.C. because of its colour resemblance to blood, for which the greek word 'haema' was used (see Deer et al. 1962, p.21).

It occurs mostly as granular or platy crystal aggregates. Colour - dark grey, occasionally with shining crystals; lustre-metallic ; streak-cherry-red ; hardness - 5.5 - 6.5.

Ore-microscopic study shows that the mineral is euhedral to subhedral martite, a pseudomorph of hematite after magnetite (Plate X, fig.3) or specular or platy hematite (Plate X, fig.4).

Colour - white or greyish white usually with a bluish tone . Reflectivity - high, highest of all iron minerals. Martite shows greyish white colour, slightly lower reflectivity and weaker anisotropism than specular or platy hematite. A plausible reason for this difference in reflectivity and anisotrophism may possibly be due to the presence of ferrous oxide i.e., sub-microscopic residuals of magnetite scattered in martite besides incipient hydration in it (see Brokerick, 1919, p.363; Gilbert, 1925, p.592).

Etch reaction :

Negative - To all standard reagent. In a few cases HF acid reveals grain boundaries.

Magnetite ($Fe^{+2}\ Fe_2^{+3}\ O_4$).- The mineral is either named after the locality Magnesia, bordering Macedonia or after Magnes who first discovered it (see Dana 1962, p.492).

The mineral is crystalline and belongs to the isometric system. Colour - steel grey to iron black ; streak - black ; lustre - metallic ; hardness - 5.5 - 6.5.

Under reflected light the granular crystals of magnetite occur as subhedral to euhedral cubes and octahedra (Plate XI,fig.1). Incomplete martitization of magnetite is almost a universal feature among the ores. Colour - pale grey with distinct brownish or pinkish tinge, Reflectivity - moderate, lower than hematite but higher than goethite. Isotropic.

Etch Reaction :

Positive - $SnCl_2$(Sat) + HCl (1 : 1), develops grain boundaries. Hot HCl (1 : 1), darkens and solution turns yellow.

Negative - All other standard reagents.

Goethite (α - FeO.OH).- The iron mineral goethite is named after the poet and philosopher Goethe (1749-1832 A.D., see Dana, 1962, p.504).

The common forms in which the mineral occurs are massive, stalactitic or botryoidal. Colour - yellowish, brownish or brownish black ; streak - yellow, brown ; lustre - adamantine; hardness - 5 - 5.5.

Under reflected light goethite is usually massive or cryptocrystalline, sometimes colloform and rarely fibrous. Fibrous goethite generally radiates from the free surface of colloform goethite. Colour - dark to dull grey. Reflectivity - low. Anisotropic. Reflection pleochroism - weak, fairly noticeable in oil but often masked by orange to red internal reflection. According to Ramdohr (1969, p.1047) this property of goethite is variable since it depends on the content of absorbed water. Internal reflection is more conspicuous in the massive goethite.

Etch Reaction :

Positive - $SnCl_2$ + HCl (1 : 1), attacts with formation of pits and becomes stained dark brown after three minutes.

Negative - All other standard reagents.

Lepidocrocite (γ - FeO.OH).- The name lepidocrocite was given after the Greek words 'lepidos' and 'krokis', meaning scales and fibres due to its similar habits (see Deer et al. 1962, p.122).

Because of its scanty occurrence in the ores it is practically impossible to study its physical characters in handspecimens.

Lepidocrocite is of rare occurrence in the ores examined in reflected light. Very careful observation is generally required to differentiate lepidocrocite from goethite. The mineral is exclusively associated with the colloform goethite (Plate XI,fig.2). In certain cases due to complete enclosure of goethite by thin lepidocrocite rim, an 'atoll' structure is developed (Plate XI, fig.3). Colour - pale grey to greyish white, often with brownish or bluish tinge. Reflectivity - higher than goethite but lower than hematite. Pleochroism - more distinct than goethite specially in oil, usually giving reddish-brown internal reflection. Anisotropism- strong in shades of grey.

Etch Reaction :

Positive - $SnCl_2$ often reveals the structure.

Negative - All other standard reagents.

Manganese Ores

Pyrolusite (MnO_2).- The names pyrolusite and polianite are often confusing and remained controversial for long, though both the minerals have identical chemical composition. Ramdohr and

Schneiderhohn (1931) suggested the name polianite for the coarsely crystalline variety and restricted the term pyrolusite to the fine-grained variety (see Dunn 1936). Orcel and Pavlovitch (1931) on the other hand used the term pyrolusite for the mineral which forms a pseudomorph after manganite, and the term polianite to the crystalline variety formed directly during the process of mineral formation (see Dunn, 1936). Based on the X-ray studies Vaux (1937) concluded that both these minerals have identical crystal structure. On the above basis Uytenbogaardt (1951) described both the varieties as a pyrolusite and discarded the use of the term polianite for the crystalline variety. Ramul (1965) differenciated polianite and pyrolusite on the basis of their forms and optical characters. The present worker observed coarsely crystalline accicular (Plate XI,fig.4) and noncrystalline varieties of pyrolusite but their optical characters are almost identical, except that the anisotropism is stronger in the case of crystalline pyrolusite than in the non-crystalline one.

Pyrolusite occurs in massive, reniform to well-developed crystalline forms. It is generally associated with the lateritic manganese ores and in a few cases with the hard iron ores. Colour - steel grey to iron black, the crystalline variety has a shining surface ; streak - dark black ; lustre - metallic to submetallic.

In reflected light colour of the mineral is white with a distinct yellow tinge; Reflectivity - high ; coarser variety

shows reflecting pleochroism particularly, in oil; Anisotropism - strong in shades of slaty grey and light yellow. Fine-grained varieties are feebly anisotropic.

Etch Reaction :

Positive - $SnCl_2$(sat), darkens immediately.
H_2SO_4 (Conc.), stains permanently.
$H_2O_2 + H_2SO_4$, stains permanently, but the reaction is more rapid.

Negative - HCl, HNO_3, KOH.

Psilomelane($Ba\ R_9O_{18}\cdot 2H_2O$, $R = Mn^{II}\ Mn^{IV}$).- Psilomelane is a general name used to define two different manganese minerals viz., psilomelane and cryptomelane. But the two manganese minerals cannot be distinguished by their physical or optical characters. Ramsdell (1942) by X-ray diffraction study found that the so called 'Psilomelane' contains 60 °/o cryptomelane and about 30 °/o psilomelane. Chemically, these two minerals differ only in two of their minor constituents, namely, Bao and K_2O. According to Mukharjee (1959) the powder pattern of the so called 'psilomelane' corresponds to that of crytomelane. The present worker had no opportunity to differentiate between psilomelane and cryptomelane by X-ray diffraction or by chemical analysis. The general term 'psilomelane' is, therefore, used in this text.

Psilomelane is generally massive or colloform. Colour - dark steel grey ; streak - brownish black ; lustre - submetallic; hardness - 6 - 6.5.

Psilomelane is of rare occurrence in the ores examined under reflected light and often associated with pyrolusite. Colour - bluish grey to greenish white. Reflectivity - higher than pyrolusite; Anisotropic in shades of grey.

Etch Reaction :

Positive - $SnCl_2$(sat), blackens instantaneously.
HCl, stains brown.
HNO_3, stains light brown.

Negative - Aqua regia, KOH, HCl_3, $FeCl_3$.

MINERALOGICAL ASSEMBLAGE

On the basis of their ore-microscopic studies, the iron and associated manganese ores of Bicholim and Sanquelim have been classified into the following four mineralogical assemblages :

Iron Ore :
- Martite-Magnetite-Goethite
- Magnetite-Hematite-Martite-Goethite

Manganiferous iron Ore : Martite-Magnetite-Pyrolusite-Psilomelane

Manganese Ore : Pyrolusite-Psilomelane

Martite-Magnetite-Goethite Ore

The ore belonging to this assemblage is massive and hard

laminated. It is by far the commonest of all the iron ore deposits of the area and composed largely of granular martite surrounded by goethite, which actually occupies intergranular spaces in the ores. Frequently, martite have innumerable unreplaced fragments of magnetite whose grain boundaries are very irregular. However, there are also some unaltered to slightly altered magnetite having well-defined crystal boundaries. The ore is generally of high grade containing about 62 per cent Fe.

Magnetite-Hematite-Martite-Goethite Ore

The ores of the above mineral assemblage are characteristically schistose and occur restrictedly in the deposits. Hematite is specular, the flakes of which due to their preferred orientation make the ore somewhat schistose. Magnetite and its pseudomorph, martite are granular and largely confined to the granulose bands which alternate with the schistose bands consisting essentially of specular hematite. Colloform or massive goethite which invaded these ores later, is insignificant in quantity and occurs only as intergranular space filling material.

Martite-Magnetite-Pyrolusite-Psilomelane Ore

This variety of ore is rather uncommon and generally composes the manganiferous iron ores which are hard and laminated. Locally, it is known as ferro-manganese ore, characterized by the presence of medium to coarse-grained martite with irregular fragments of magnetite. Interstitial spaces of these martite -

magnetite are filled with colloform pyrolusite and psilomelane. On the average this ore-assemblage contains about 30 per cent of manganese dioxide as determined by chemical analysis.

Pyrolusite-Psilomelane Ore

This manganese ore occurs scattered in irregular small pockets associated with the lateritic caprock over the hard laminated iron ores. Pyrolusite is more frequent than psilomelane. The ores are generally botryoidal indicating their colloform nature. Some crystalline pyrolusite occur either in vugs within or on the free surface of the colloform ores.

TEXTURES AND MICROSTRUCTURES

The iron and manganese ores of Bicholim and Sanquelim have several interesting and characteristic textural features. Banded structure and granular texture are very characteristic in most ores having martite and goethite as their essential constituents. In addition, colloform and replacement textures of various types are evidences of secondary ore deposits (see Schwartz, 1951). In a few cases due to preferred orientation of specular hematite, some magnetite and gangue, the ores appear schistose.

Banded Structure

The banded structure, which was the depositional feature of the protore is ideally retained by the hard and laminated iron ores consisting essentially of euhedral grains of martite

with some magnetite and massive goethite. The banding in these ores is quite conspicuous under the microscope (Plate XII,fig.1). Thin trains of goethite in some ores also serve to distinguish banding (Plate XII,fig.2). Sometimes the bands are slightly deformed. Veins of gangues or goethite occassionally cut across these bands.

Granular Texture

Granular texture is typically displayed by the ores which are largely made up of subhedral or euhedral magnetite and martite crystals with some goethite occupying the intergranular spaces (Plate XII,fig.3). When the iron ore is manganiferous, pyrolusite occurs in the interspaces of martite and magnetite, instead of goethite (Plate XII,fig.4), and in the case of protore, silica is the chief intergranular material (Plate XIII, fig.1). Generally magnetite or martite is equigranular.

The granular pyrolusite in the manganese ores exhibits mosaic texture in which the individual subhedral grains are interlocked with one another (Plate XI,fig.4).

Schistose Structure

The schistose structure is developed in a few of the hard iron ores which are composed of magnetite-martite and specular hematite with some gangue. Specular hematite shows preferred orientation of its grains (Plate XIII,fig.2). Imperfect preferred

orientation of the associated gangue minerals also occasionally serves to recognise crude schistosity. Similarly, magnetite or martite crystals also show preferred orientation of their grains(Plate XIII,fig.3).

Colloform Texture

Colloform texture was commonly observed in the lateritic manganese ores and rarely in the iron ores. The ores showing this structure are composed of a series of concentric bands of pyrolusite and psilomelane (Plate XIII,fig.4). The curvature of the bands are towards the younger free surface (see Edward, 1960, p.20). Some of the ores developed very smooth concentric bands while in others they are irregular. In a few cases there is small nucleus of ore or gangue around which concentric bands of pyrolusite and psilomelane occur (Plate XIV,fig.1). Occasionally, well-developed needles of accicular pyrolusite has a rediating pattern in the vugs (Plate XIV,fig.2). These colloform bands have also some radial shrinkage cracks. Colloform texture is, however, not common in the iron ores. The texture was only shown by the colloform variety of goethite having rare association of lepidocrocite (Plate XI,fig.2).

Replacement Texture

Replacement textures are very frequently developed in the hard laminated iron ore and less commonly, in the manganese ores. Among them pseudomorphic replacement of magnetite by martite

(Plate XIV,fig.3), and occasionally, by goethite (Plate XIV, fig.4) is most prevalent. The texture is of special significance since it gives direct clue to the paragenetic sequence of the ore minerals or group of minerals.

In general initial pseudomorphic replacement starts along grain boundaries (Plate XV,fig.1), cleavage parting (Plate XV, fig.2), fracture planes, etc.. The various types of replacement textures observed in the ores are : pseudomorphic replacement, relict and vein textures.

TEXTURAL RELATIONS AND THEIR INTERPRETATION

Various textural features,observed in the iron ores and some associated manganese ores,furnished valuable information regarding the textural relations of the ore minerals which ultimately helped to establish their sequence of formation and processes involved therein. The iron ores are predominantly composed of hematite and goethite. Magnetite is a subordinate constituent. Lepidocrocite in these ores is still very insignificant and rare. Among the manganese minerals pyrolusite is more common than psilomelane.

The rare schistose variety is often characterised by the presence of distinctly schistose bands of flaky hematite alternating with those of granular martite. The iron minerals occupying intergranular spaces in this variety of ore is goethite. Most of the martite crystals have minute relicts of magnetite which indicate incomplete chemical alteration of magnetite into martite

(Plate XIV,fig.3 and Plate XV,fig.3). Specular hematite is somewhat oriented in the direction of schistosity of the ore (Plate XIII,fig.2). There is no evidence to believe that martite is earlier or later than specular hematite in their relative time of appearance. The segregation of martite and specular hematite in alternate bands indicates that the two iron minerals are contemporaneous. Further, occasional presence of straight boundary relation between magnetite and specular hematite (Plate XV,fig.4) is also an additional support in favour of the above view.

The hard laminated ore also consists of magnetite, martite and goethite. Careful observation often shows crude lamination in these ores. Occasionally pseudo-lamination is indicated by thin trains of goethite following laminae of the ore (Plate XII, fig.2). Individual laminae of the ore is composed of martite grains which vary in size from 0.1 mm to 0.3 mm and embeded in a groundmass of goethite (Plate XIII,fig.1) or gangue (Plate XII, fig.3). Granular texture is/the characteristic of these ores. Pseudomorphic replacement of magnetite by martite was most prevalent. Initial martitization generally starts from the grain boundaries of magnetite forming an irregular rim of hematite which gradually advances inward in the form of thin lamellae following the octahedral cleavage partings of magnetite (Plate XV,fig.1 and Plate XV,fig.2) due to which such martites show well-developed widmanstetten like texture.

Gruner (1926a, p.378,386) has experimentally shown that a

polished surface of magnetite does not oxidize unless the surface is parallel to the octahedral plane. He advocates that for oxidation of magnetite into hematite, oxygen atom must enter into the crystal lattice of the former so that ferrous atom may convert into ferric atom.

With prolonged oxidation hematite lamellae in magnetite become wider thus decreasing the magnetite area between them. In an advanced stage of oxidation there remain only a few relicts of magnetite (Plate XIV, fig.3). In certain cases the replacement is so complete that hardly any relict of magnetite is left in martite (Plate X, fig.3).

Goethite, which occurs as an intergranular space mineral, is either massive or colloform. To some extent this goethite also replaces martites (Plate XVI, fig.1). Occasionally, the colloform variety of goethite is encircled by rings of lepidocrocite showing an 'atoll' like texture (Plate XI, fig.3).

The rate of oxidation of magnetite also is not uniform as could be seen from the fact that in certain cases oxidation is more complete than in others. The rate of oxidation, however, depends upon several factors like grain size, degree of perfection of crystal lattice and the origin of magnetite. It seems in the case of smaller grains that oxidation is faster probably due to the fact that smaller grains have larger surface energy than the larger grains (see Gruner, 1926a, p.379-380 ; Leep, 1957, p.679). Gruner (1926a) further stated that magnetites

of sedimentary origin are more susceptible to oxidation than those of magmatic segregation and contact metamorphic origin.

A very rare case of pseudomorphic alteration of magnetite into goethite in preference to direct martite formation was noted in a few ores. Although usually relicts of magnetite is absent yet the characteristic crystal shape of magnetite has been beautifully preserved (Plate XVI,fig.2). Occasionally, however, goethite is seen replacing magnetite irregularly having some relicts of the latter in the former (Plate XIV,fig.4). The greater tendency of magnetite to alteration into goethite than that of hematite provides an explanation for the above fact (Girbert, 1925, p.595). Subsequently, these goethites are also replaced by martite following octahedral cleavage planes of the original magnetite, resulting wedmanstetten like texture (Plate XVI,fig.3).

Various stages of oxidation of pseudomorphic goethite into martite were recognised in these ores. At the initial stage only a few thin streaks of hematite along the margin of goethite serve to recognise the feature but with gradual advancement of oxidation an irregular rim of martite with goethite in the core is often distinct (Plate XVI,fig.4). Massive or colloform goethite, which occurs mostly within the intergranular spaces of martite, is distinguishable from pseudomorphic goethite by its lighter grey colour and distinctly red internal reflection. Moreover, in a few cases,colloform goethite also replaces the goethite pseudomorphs after magnetite (Plate XVII,fig.1).

It may be pointed out here that the pseudomorphic alteration of magnetic into goethite was commonly observed in the silica-rich iron ores or in protore.

The manganiferous iron ores, which have a common assemblage of martite, pyrolusite and psilomelane also resemble texturally the hard laminated iron ores. Martitization in these ores is generally incomplete and as a result of which martite have many irregular relicts of magnetite. Colloform pyrolusite and psilomelane usually occupy intergranular spaces (Plate XVII, fig.2). These manganese minerals, in certain cases, also replace martite grains but marginally (Plate XVII,fig.3). In a few cases there are regular colloform bands of pyrolusite, psilomelane and goethite (Plate XVII,fig.4). In some other cases goethite is either veined by pyrolusite or irregular patches of goethite occur in pyrolusite indicating replacement of the former by the latter mineral.

The lateritic manganese ores have an assemblage of colloform pyrolusite and psilomelane occurring in the form of concentric or linear bands (Plate XIII,fig.4 and Plate XIV,fig.1). The prismatic and subhedral variety of pyrolusite generally occupies the vug walls and oriented perpendicular to the free surface of the colloform ores (Plate XI,fig.4). Occasionally, the crystalline variety of pyrolusite shows mosaic texture (Plate XI,fig.4).

DISCUSSION

The discussion is concerned with the following two important

topics : (1) Origin of martite and (2) martite-goethite relation.

Origin of Martite

Pseudomorphic alteration of magnetite into martite was reported from many iron ore districts of the world but frequently it was questioned as to whether the ascending hydrothermal or descending meteoric water was responsible for such an alteration. Newland (1922) was probably the first person to express doubt on the supergene origin of martite. Gruner (1930, p.679, 837-867) has shown experimentally that magnetite oxidised to hematite in the presence of steam or water at about 258°C. This ultimately led him to conclude that martitization was related to hydrothermal oxidation and thus considered martite to be a hypogene mineral. On the other hand Broderick (1919), Geijer (1931), Spencer and Percival (1952), Kalliokoski (1965), Teodorvich (1961) and several others cited examples of magnetite altering to hematite under supergene conditions. Therefore, according to the above mentioned workers martitization of magnetite is possible under hypogene as well as supergene conditions, though there is a greater tendency of opinion in favour of supergene origin of martite particularly, in the case of metasedimentary iron ores.

Besides the textural features, as observed under ore microscope, depth relation of the ore is another important criterion which must be taken into consideration (see Bastin 1950, p.53). So far as the depth relation is concerned it has already been pointed out by the author that there is a gradual increase of magnetite downwards which obviously indicates that the alteration of magnetite into martite is more complete on the surface than at depth.

The martite in the present case has been considered as a supergenic iron mineral not only because of its more frequent occurrence near the surface than at depth but also on account of its intimate association with goethite of secondary origin.

Martite - Goethite Relation

Although, a considerable amount of experimental work has been done so far by Posnjak and Merwin (1922), Gruner (1930), Smith and Kidd (1949) and others to establish the relation between goethite and hematite, yet their exact natural relationship is still uncertain. Gruner (1930, p.715) on the basis of his experimental finding inferred that,

> limonite is stable in the presence of water and under corresponding pressure at temperatures which approach 300°C.

But on the basis of results obtained earlier by Posnjak and Merwin (1922), Tunell and Posnjak (1931a) criticised the work of Gruner (1930). On the contrary, they (1931a) concluded that the transition temperature between gœthite and hematite in a binary system Fe_2O_3 - H_2O is approximately 130°C. By another experiment they further found that goethite in a very weak HCl solution (N/10) decomposed to hematite at 100°C.

Gruner (1931, p.443), in his later experimental work, observed that goethite is unstable at 250°C, 300°C as well as at 200°C. Tunell and Posnjak (1931b, p.898), however, admitted that this observation of Gruner is nearly in accordance with their findings.

Smith and Kidd (1949) also investigated the stability relation of hematite and goethite in a neutral and alkaline solution under pressure. Their observations show that the decomposition temperature of goethite in alkaline solution is about $150^{\circ} \pm 20^{\circ}C$. They also concluded that the temperature at which goethite decomposes is insensitive to pressure as high as those found in the earth where the decomposition temperature prevails.

From the above discussion it may now be stated that decomposition temperature of goethite in acidic solution is nearly $100^{\circ}C$, in alkaline solution it is about $150^{\circ}C$ and in neutral solutions nearly $130^{\circ}C$ irrespective of the pressure. Thus, it appears that only the qualitative effect of pH may play some role in the alteration of goethite into hematite, in other words, with increasing pH dehydration temperature of goethite also increases and vice-versa.

The possibility of alteration of goethite into hematite under supergene condition was reported by Gruner, 1922a; Bose, 1958 ; Ruckmick, 1963 ; and Chatterjee, 1964. But, the peculiar alteration of the pseudomorphs of goethite after magnetite into martite showing well-developed widmanstetten like texture has not yet been reported so far by any of the earlier workers.

Under the supergene condition of enrichment of iron ores it is difficult to account for a temperature of the order of $130^{\circ}C$ required for dehydration of goethite in a neutral solution.

Therefore, the author thinks that some reaction of organic acids derived from decaying vegetation on the iron ores (see Park Jr., 1959, p.582) as well as long exposure of the near surface ore to the atmosphere might have been the cause of dehydration of goethite into hematite under supergene condition (see Ruckmick, 1963, p.231). In support of the above remark it may be stated here that all such cases of dehydration of goethite into martite are restricted to the near-surface or crustal iron ore.

PARAGENESIS

It is evident from the foregoing discussion on textural relation of iron minerals in the schistose ores that the specular hematite and those associated magnetites which show preferred orientation and straight boundary relation with specular hematite are primary minerals and hence, earliest to appear. In absence of any replacement relation between the two minerals they have been considered as contemporaneous. Among these primary minerals, magnetites have suffered extensive chemical alteration into hematites, which are included in the second generation of hematite (martite). To a limited extent magnetite has also altered pseudomorphically into goethite. From their textural relations this stage of development of goethite was deduced to be first generation and almost contemporaneous with the second generation of hematite in the time sequence. However, unlike martitization, goethitization appears to be a very uncommon process since

goethite of the first generation occurs very restrictedly. Thus, an overlapping age relation between hematite of the second generation and goethite of the first generation is envisaged. The first generation of goethite further shows evidence of pseudomorphic replacement by hematite. The age relation between two types of martite viz., one derived from magnetite and the other, from goethite, is not very clear. However, the martite associated with goethite should be later than the martite pseudomorph after magnetite if goethitization and martitization of magnetite are taken to be paragenitically overlapping or even contemporaneous. Consequently, then this later martite becomes the third generation of hematite.

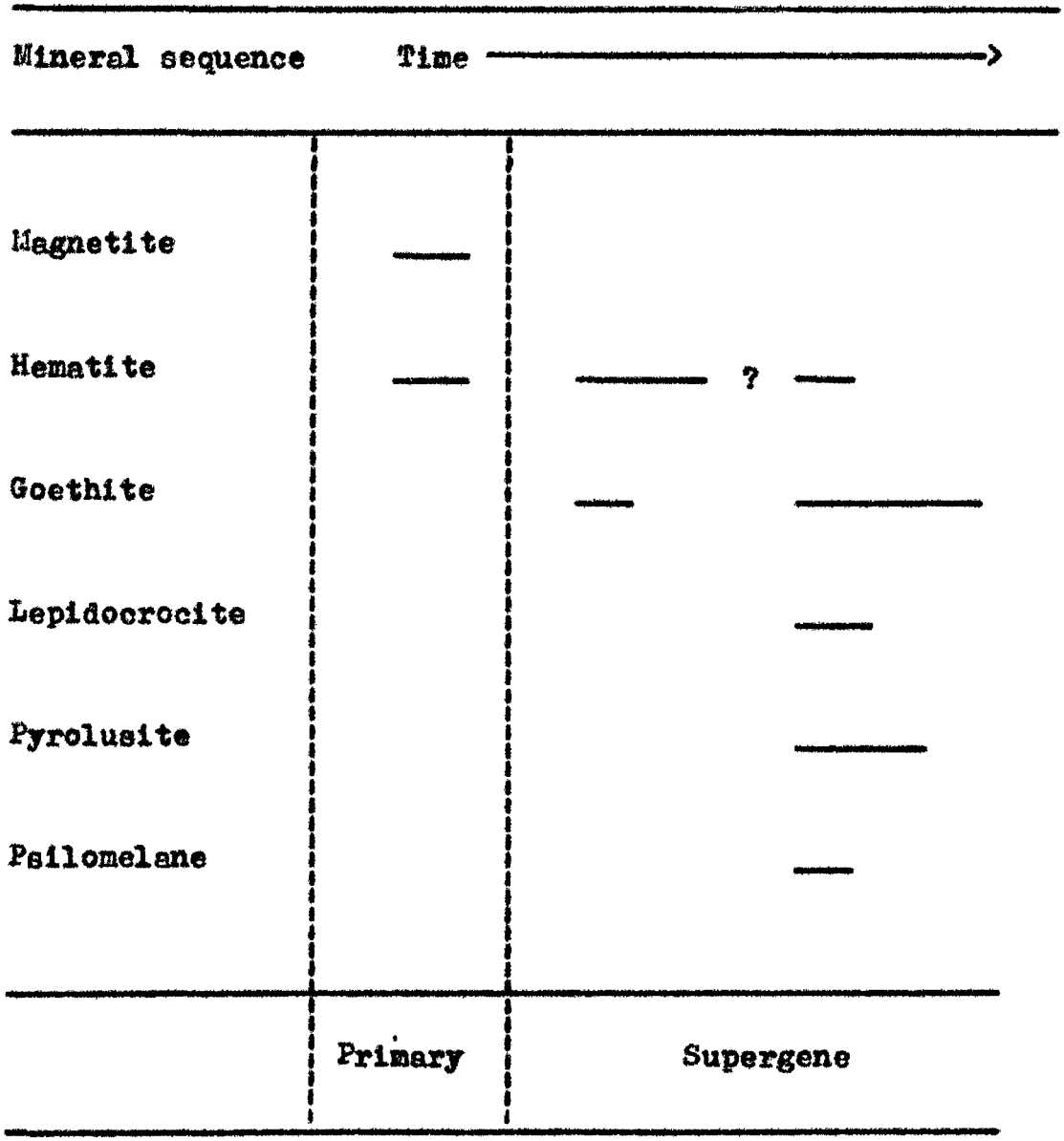
The second generation of massive or colloform goethite was not only found to occur in the intergranular spaces of martite but also to replace the latter to a limited extent. Rings or bands of lepidocrocite always occur in association with colloform goethite, suggesting that both of them are contemporaneous.

Also, pyrolusite to some extent has replaced and even veined martite and goethite of later generations but in some other cases colloform bands of goethite are juxtaposed in pyrolusite and psilomelane. It is, therefore, evident that their age relation is overlapping.

The paragenetic mineral-time sequence of the iron and manganese minerals is presented in Table V.

TABLE V

Paragenetic sequence of the
iron and associated manganese minerals of
Bicholim and Sanquelim



Chapter VII

GENESIS

The genesis of the Precambrian iron ores is such a topic of discussion that it warrants first an understanding of the origin of iron formations, or the so-called protores of iron.

IRON FORMATIONS

The Precambrian iron formations of the area, which are characteristically laminated, have been recognised from other parts of India as well as from many other countries of the world. The thick-bedded iron formation of Precambrian age was also reported from some countries (see White, 1954; Gunderson, 1960).

Terminology

So far as the terminology of the iron formations is concerned there is no general agreement among the geologists. Most of them generally prefer to follow the regional nomenclature for the various iron ore formations of the world such as jaspilite, taconite, calico-rock, itabirite, banded hematite-quartzite, etc.. An International Committee, set up by the United Nations to survey the world's iron ore resources, proposed that all iron ore formations of the Precambrian age and the ores derived from them may be termed as 'Lake Superior type', while those of younger age may be designated as 'minette type' resembling the minette ore of Lorraine, France (see Blondel, 1955). However, the Indian Geologists still prefer to use the

regional term, banded hematite-quartzite or banded hematite-jasper for the Precambrian iron formations of India. Fermor (1909, p.808) was probably the first among the geologists of the Geological Survey of India to propose the term banded hematite-quartzite or banded hematite-jasper while describing the iron ore bearing rocks of Jabbulpore district in the Madhya Pradesh state of today. Since then, both the terms are in vogue in Indian literature . Percival (1931,p.190) used the term banded hematite-jasper for the iron bearing formations of Bihar state. Jones (1934,p.196) preferred to redesignate them as banded hematite-quartzite because finely crystalline quartz or cherty quartz is interbanded with iron oxides mostly, in the form of hematite.

In spite of some controversy over using the terminology there is a general agreement that banded iron formations of Bihar and Orissa states resemble closely the 'jaspillites' of Lake Superior region, 'itabirite' of Brazil and 'calico-rock' of South Africa, etc.. (see Dunn, 1941 ; Spencer and Percival, 1952 ; Krishnan, 1955).

Problem of the Iron Formations

The typical Precambrian iron formations are widely recognised from many countries of the world including India. Remarkable similarity in their structures, primary mineralogy and modes of occurrence convinced many geologists to believe that some special condition must have been prevailing at a remote period

which never repeated exactly to the same extent later in earth's history. Iron formations similar to those of the Precambrian however, were indeed either absent or rarely reported from any other subsequent geological periods as for example O'rourke (1961) reported iron formations from early Paleozoic of Nepal. Moor and Maynard (1929,p.526) wrote :

> The conditions of formation of these banded formations must be peculiar to the pre-Cambrian era, since no deposits exactly similar have been formed in later eras although they were deposited on every continent in that era.

Most of the authorities, who have deeper knowledge of the geology of Precambrian iron formations, considered tham as chemically precipitated marine sediments. But, the subjects on which they differed were the source of iron and silica, their mode of transportation, origin of banding, Precambrian atmosphere and the physico-chemical changes that occurred during and after their deposition.

Volumes of literature on the subject and its problems have accumulated to date. It is apparent from many of these works that two different views were expressed as regards the source of iron and silica in iron formations and which may be stated as follows :

1. Submarine magmatic or volcanic sources poured their iron and silica contents which were deposited on the sea floor as banded iron formation.

2. Iron and silica were disintegrated from the volcanic land masses neighbouring a sea due to various weathering

processes. Subsequently, brought down in solution, they have been deposited rhythmically on the sea floor either directly as a chemical precipitate or through organic agencies.

Acceptance of any one of the above view in preference to the other obviously depends on the approach to the problem and also on the geological evidences available from a study of the iron formation in question. There are, however, still important arguments for and against the two views. Accordingly, there is no reason to believe that a single theory of origin should explain or be applicable to all such formations the world-over.

According to Hogg (1961), iron formation of volcanic source was accumulated first in early Precambrian times and true sedimentary types were derived from it later by processes of weathering. In spite of oversimplification of the problem of origin by Hogg, the subject continues to be enigmatic as there are many intricate geological and geochemical problems which must be solved before accepting his view.

A Review of Literature

There is a large number of literature dealing with the problems of iron formation, especially relating to the source of iron and silica, in addition to the origin of banding and other related problems. Some of the important works are briefly reviewed as follows :

In their discussion, Van Hise and Leith (1911) advocated Volcanogenic origin for the Lake Superior iron ore deposits. They were of the opinion that to a large measure iron and silica were contributed by magmatic water from the contemporaneous igneous rocks and to a lesser extent, by the reaction of the sea water with submarine hot lava flows.

According to Gruner (1922b), the greater part of iron and silica was derived from basaltic and greenstone land masses by normal process of weathering. He also postulated that climate of the period was humid and tropical or sub-tropical with abundant lower forms of vegetation which aided rapid decay of rocks. Under such favourable conditions iron and silica went into solution and being stabilized by organic colloids, they were carried to the sea by rivers rich in organic matter. Precipitation was caused chiefly by algae and bacteria in the basin of accumulation.

Gill (1927) believed that at least in part, the origin of Gunflint iron formation is similar to modern gluconite deposits. He suggested the decomposition of iron bearing silicates from a landmass of moderate relief with temperate or tropical climate was chiefly responsible for supplying iron and silica. These decomposed products were carried to the sea by rivers as colloids and stabilized by protective agents. The clastic sediments were deposited near the river mouth but the sols, retaining their stability, were carried far off to the site of deposition

by off-shore currents. Mingling of solution from different sources was considered to be the chief factor for the precipitation of iron and silica. During or shortly after the precipitation, bulk of the precipitates consisting of galatinous iron and silica were chemically rearranged. Thus, hydrated ferrous silicate and silica, hydrated ferric oxide and silica, and in some places mixtures of all these substances formed the final product. Ferrous carbonate was formed locally by a reaction between hydroxide or greenalite and some organic matter.

Moor and Maynard (1929), assuming abundance of organic matter in the Precambrian times suggested that extraction and transportation of iron and silica from igenous rocks might be possible in cold water. Under such condition iron will be dissolved and carried as ferric oxide hydrosol and the silica as colloids, and both, being stabilized by organic matter, would be precipitated by the electrolytes of the sea. The banding in these deposits might be due to differential rate of precipitation of iron and silica on account of varying proportion of the material brought into the basin of deposition during seasonal changes.

Dunn (1935, 1941) expressed the view that the banded iron formations were originally deposited as fine-grained ferruginous tuffs and iron-rich sediments. More or less contemporaneously, they were oxidized and silicified under the action of solutions which were partly magmatic. The silification gave rise to the

banded cherts and jaspers that alternate with iron-rich layers. Percival (1931) also expressed a similar view.

Woolnough (1941) expressed the opinion that the world's banded iron formation of the Precambrian period represented epicontinental sediments formed as chemical precipitates. Peneplanation of continental areas provided numerous isolated depressions as well as optimum environment for the production of cold natural solution which dissolved the rock forming minerals. In this condition the dissolved materials were carried by streams in isolated closed basins within which precipitation of colloids proceeded undisturbed by water currents and without the admixture of appreciable quantity of clastic sediments. Banding, as he explained, was due to the seasonal and successive accession of silica and iron solutions.

According to Alexandrov (1955), the banding in the Precambrian iron formations was due to selective weathering of some Precambrian basic rock rich in iron bearing silicates. The chief factors facilitating such selective weathering were seasonal changes in temperature, amount of precipitation and alternately high and low pH of the leaching solution. He also suggested that the solution entering into the basin of deposition were exclusively charged with iron in the cool and chiefly with silica in the warm season. Such seasonal variation in the quantities of iron and silica brought into solution was also suggested by Sakamoto (1960).

James (1954) suggested that the iron bearing solutions were derived from the deep chemical weathering of the continents. The major environmental requirement for the deposition of iron formation in such a solution is a close or restricted basin. The required basin was formed during the development of a geosyncline. He further expressed that relationship between volcanism and sedimentary iron formation is structural and not chemical i.e., both are associated with the geosynclinal development. According to James (1954) these close associations were rather accidental and hence, iron formations could not be connected genetically with volcanism.

Goodwin (1956) held the view that the source of iron and silica of Gunflint iron formation was related to volcanic exhalation and that they were deposited in a marginal basin bordering open sea. Volcanism in one hand steadily supplied iron and silica bearing solution and on other hand induced cyclical fluctuation of the basin of deposition. Consequently, the development of iron formation was due to cyclic sedimentation.

Huber (1959) considered the iron formation of Michigan as a product of chemically precipitated marine sediments. According to him iron and silica bearing solution were derived from continental land masses.

Hough (1958) postulated that the iron and silica in the banded iron formation of Lake Superior district were principally derived from deep weathering of continents under sub-tropical to warm temperate climate with moderate to high rainfall. Iron

and silica deposited alternately during the cooler and warmer seasons of the year. The basin of deposition was large, sufficiently deep and a fresh water lake permitted density stratification of the water during the summer. The lower water layer in summer was isolated from the atmosphere having a slightly reducing and acid condition in which iron was kept in solution, while silica was precipitated. During the winter when the oxidizing and alkaline water was in complete circulation, iron was precipitated in the ferric state. Govett (1966) also expressed a similar view to account for the origin of banded iron formations.

Leep and Goldich (1964) advocated that during the early Precambrian period there was a marked deficiency or absence of free oxygen in the atmosphere. Weathering under such a condition permitted transportation of iron, silica and manganese. They were also of the opinion that a critical level of free oxygen was attained permitting acceleration of plant growth and accretion of oxygen. This unique condition effectively curtailed the development of characteristic Precambrian iron formation in later geological periods.

Prevailing oxidizing condition and absence of continental flora during early Precambrian period was considered by Schweigart (1965) to be unfavourable for normal lateritic weathering and transportation of solution in the basin. Therefore, he expressed the opinion that the iron and silica were contributed by acid submarine volcanic exhalations from time to time into the basin of deposition.

Regarding the origin of the Australian jaspilites, Liddy, (1968) believed that the iron and silica hydrosols were deposited cyclically within the carbonate water of still and shallow marine basin. Later the deposit was lithified. He, however, held the source of iron and silica as debatable although related the ancient landmass to them.

McLeroy (1970) discussed the genesis of the iron ore deposits of New Mexico and held the view that the iron deposits of Cleveland Gulch and Iron Mountain differed genetically from the other banded iron deposits of the world. On the basis of field and laboratory evidence he concluded that the deposits were formed from hydrothermal solution by selective replacement of the pre-existing banded metamorphic rocks.

Sources of Iron and Silica

It is evident from the previous references reviewed in the foregoing paragraphs that the source of iron and silica in the Precambrian iron formation is still questionable. Generally, the source has been attributed either to direct volcanic contribution or to weathering of contemporaneous basic igeneous terrain. It was generally agreed by Gruner, 1922b; Gill, 1927; Moor and Maynard 1929; Sakamoto, 1950; Leep and Goldich, 1964; Alexandrov, 1965; Huber, 1959; that the iron and silica in the iron formations have been leached and derived from igenous terrain of low relief that was approaching almost peneplanation.

Most of them were of the opinion that the tropical or subtropical climate was responsible for such a chemical decay. Woolnough (1941), however, advocated weathering in arid climate. James (1954,p.276) pointed out that

> under certain tropical or subtropical conditions the iron and silica contents of stream water may be very high and entirely adequate to account for iron-formation deposition.

All the above workers also have unequivocally attributed weathering of pre-existing landmass to the source of iron and silica.

On the other hand among those who proposed that iron and silica were contributed by submarine volcanic source , mention may be made of Van Hise and Leith (1911), Percival (1931), Dunn (1935, 1941), Goodwin (1956) and Schweigart(1965).

A perusal of the field evidence relating to the iron formations of the area under study reveals that there is no such occurrence of contemporaneous volcanic rocks which may be related genetically to the deposits. There are only some sporadic basic dykes which indicate milder volcanic activity. In the absence of any evidence of volcanogenic source the author is inclined to support the view in which the ancient landmass was held responsible for the supply of iron and silica through weathering in a humid and tropical climate.

Iron.- Van Hise and Leith (1911) pointed out that the weathering processes could not account for the Precambrian iron formation because of relative insolubility of iron in the ferric state under the present day condition of lateritization.

Gruner (1922b), among many other proponents of weathering as a source of iron, also realised this fact and suggested that iron might have been transported either in a ferric or ferrous state under an 'abnormal' Precambrian environment. Moor and Maynard (1929) considered that iron was transported as a hydrosol stabilized by organic matter. According to Cooper (1937), iron under reducing condition and having a pH value of 6 is 100,000 times more soluble than under oxidising condition at a pH of 8.5.

As regards the transportation and preceipitation of iron concerned with the present case the author can only say that due to preponderence of ferrous over ferric oxides in the iron formations, the state, in which iron was transported and precipitated was probably ferrous-ferric (see James, 1954, p.242) or might be ferrous (see Goodwin, 1956, p.590).

Silica.- Silica, mostly in the form of chert or fine-grained quartz, is the other principal constituent of the iron formation in question as well as in most Precambrian iron formation of the world. As regards its origin, James (1954), White (1954) and Huber (1959) expressed the view that cherts were primary because such sedimentary features as slump structure, intraformational conglomerate, stylolites, etc., are sometimes found in them indicating that they were contemporaneous with sedimentation.

On the contrary Dunn (1941), Leep and Goldich (1964) favoured replacement origin of chert. The former author cited

some evidence of silification of tuffs in support of his view while according to the latter authors large scale silification of carbonates in the earlier sediments provided the evidence of replacement.

Silica in natural water can exist either in true solution i.e., as $H_4 SiO_4$ or in a colloidal state (see Krauskopf, 1967, p.166). Works of Alexander et al.(1954) and Krauskopf (1956) indicate that the solibility character of silica in the pH range between 0 and 9 has no effect but the solibility increases sharply as the pH rises above 9 because of the ionization of H_4SiO_4. Besides the pH, other controlling factors of the solibility of silica in a natural system are the type of ionic bonding, size and pressure-temperature relationship (see Degens, 1965, p.76).

As regards the precipitation of silica, Gruner (1922), Gill (1927), Tyler and Twenhofel (1952) held the view that organisms like diatoms, radiolaria, etc., of the depositional basin played an important part. Their conclusion is based mainly on the discovery of algal structure in some Precambrian banded chert. It may be pointed out here that Spencer and Percival (1952, p.380) also recognised some micro-structures from the banded jaspers of Singhbhum district of Bihar, India, which are akin to Gruner's algal structure, but they considered them as inorganic spherulitic structures.

Krauskopf (1956) on the other hand suggested that due to absence of silica secreting organisms, silica content in the

Precambrian sea was much higher than in the modern sea. Inorganic precipitation of silica in the Precambrian sediments was therefore envisaged. Siever (1957) also expressed a similar view regarding inorganic precipitation of silica in ancient sea. Huber (1959, p.113) suggested that iron and silica in solution could be transported well into the depositional basin where they would precipitate inorganically after attaining saturation, whereas the clastic materials would be discharged near the shore.

In the light of above discussion, an attempt is made hereunder to account for the silica in the iron formations under review :

1. As on one hand a clear-cut evidence of the primary origin of chert like slump structure, stylolite, etc., is lacking so, on the other hand, any carbonate mineral or of its pseudomorph, which could be an index for replacement phenomenon, is also absent. As such, there is no positive evidence to believe that cherts are of replacement origin.

2. Such a primary sedimentary structure as alternate banding of cherty quartzite and iron oxide minerals and their remarkable parallelism suggested that both iron and silica were deposited together rhythmically.

3. Apparent constancy of the amount of chert in the iron formations over a wide area like Sirigao-Bicholim deposit is also consistent with the above arguments.

Restriction of Occurrence and Banding in Iron Formations

As a solution to the problem of restriction of the iron formations to Precambrian period many workers held the view that the Precambrian atmosphere was deficient in oxygen and rich in carbon dioxide. Under such atmospheric condition more iron was likely to be taken into solution in a ferrous state than under normal condition. They also thought that this special atmospheric condition never repeated in later geological periods thus, restricting the iron formation to the Precambrian period. (MacGregon, 1927; Sakamoto, 1950; Leep and Goldich, 1959). On the contrary some other workers believed that no such special condition was necessary to account for the deposition of iron formation during the Precambrian particularly because there are also some instances of iron formations belonging to the Palaeozoic (see Rubey, 1951; James, 1954; Schweigart, 1954; Govett, 1966). According to Sakalov (1959) and Urey (1954) the primitive atmosphere was composed of CH_4, H_2, CO, H_2 and H_2, CH_4, NH_3 respectively.

Woolnough (1937) and James (1954), without calling upon the primitive atmosphere to explain for the restriction of iron formation, suggested that a combination of the longer period of crustal stability, exceptionally deep peneplanation of the ancient land mass faciliting higher degree of chemical weathering and a closed and restricted basin of deposition provided an ideal environmental condition during the Precambrian period

and which never repeated except for a short time during the early Paleozoic. They thought that the above conditions restricted the iron formation to the Precambrian period.

There is also a diversity of opinion with regard to the banded nature of Precambrian iron formations. Moor and Maynard (1929) attributed banding to the differential rate of precipitation. Banding due to alternate deposition of iron and silica corresponding to seasonal changes was advocated by Sakamoto (1950) who further postulated that ferrous iron was transported in acidic solution during wet seasons and precipitated when it was neutralized. Silica, on the other hand, was transported in an alkaline medium and precipitated under acidic environment. The idea of seasonal variation as a factor controlling the supply of iron and silica in different proportions was also put forward by Woolnough (1941). Huber (1959) believed that a cyclical variation in the activity of organism may provide a reasonable explanation for the banding. Tyler and Twenhofel (1952) accounted for the general absence of stratification in the present day lake deposits as due to the activity of mud-eating or mud-dwelling organisms. Accordingly, they felt that the deposits during the Huronian time could possibly have retained their laminations because of the absence of any such organisms.

The lithological character of the iron formations of the area under review, shows that they generally consist of very thin, regular and more or less persistent bands of iron and

silica in alternate positions. Individually, the bands vary in thickness from 0.5 mm to 3 mm or slightly more. Since, the lithology of this iron formation simulates many such deposits described from other parts of the world, the present worker is inclined to accept the belief that seasonal variation in the quantities of iron and silica in solution, probably coupled with the absence of organism in the depositional basin, was responsible for the laminations in the iron formations.

Environment of Deposition

It has generally been accepted that iron formations are epicontinental sediments deposited in a restricted marine basin. According to several investigators (Krumbein and Garrels, 1952; Huber and Garrels, 1953; James, 1954; Huber 1958) the nature of primary iron minerals which are present in the sediments reflects the environmental condition of deposition, and the formation of a particular iron mineral or group of minerals depends on a particular set of physio-chemical condition.

Physical Factors.- The physical parameters are shape and stability of the basin, depth of water, closeness to the shore, degree of circulation, etc. (see Huber, 1959). As an example of relationship between physical parameters and the type of iron minerals precipitated, a statement of Hotchkiss (1919, p.446) is quoted as follows :

> ... it is believed that the wavy-bedded members of the iron formation are relatively shallow water deposits in which the bottom was within reach of the action of waves that disturbed the bottom and produced the wavy-bedded structure, and the water contained abundant oxygen to oxidize the iron as was deposited. The even-bedded portions of the formation are believed to have been deposited in deeper water where the bottom was below the reach of wave action and contained so little oxygen that the iron could persist as carbonate.

James (1954, p.242, Fig.3) illustrated diagrammatically that on a wave and current-swept shelf, iron must precipitate in a ferric state because of the abundance of oxygen. In the deeper parts of the basin, H_2S would be formed by the bacterial action leading to the precipitation of iron as sulphide. At intermediate depth, lying between the two, there would be enough oxygen to prevent the formation of H_2S. He, therefore, suggested that iron would have a greater chance to precipitate in this intermediate zone either as ferrous carbonate or as magnetite.

Iron formation developed under low oxidation potential suggests restricted condition and lack of aeration of the basin. An elongated basin marginal to an eroded land mass or a shallow and relatively tideless epicontinental sea would probably be the best environment to fit the above requirements (see James, 1954, p.279; White, 1954, p.52). The same two authors as above, have also pointed out that chemical as well as clastic sediments may be deposited simultaneously in a single basin or shelf area. The type of contemporaneous deposits at any locality would depend on various factors but the most important one is probably

the increasing distance from the shore line with which there is a gradual change in the depth of water, aeration and transportation of clastic meterials.

Several other workers believed that iron formations were deposited under fresh water lacustrine or closed-basin environment rather than marine (see Tyler and Twenhofel, 1952; Hough, 1958; Govett, 1966). Hough (1958, p.419) stated that

> The Eh and pH values required for deposition of all of these iron minerals are within the ranges which occur in fresh water lakes.

Their chief argument against marine origin based upon the paucity of calcium carbonate and abundance of ferrous carbonate in the carbonate iron formations.

Based largely on the views expressed by the previous workers and also on the nature of the sediments in his own area, the author favours a marine origin for the iron deposits of Bicholim and Sanquelim, and presents his chief arguments as follows :

1. There is no carbonate of iron in the iron formation itself or the associated rocks.

2. Coarse clastics and poor sorting, which are assignable to continental deposits, are remarkably absent in the iron formation as well as in associated rocks.

3. The iron formations are often interbedded with typical pelitic sediments of geosynclinal phase like those of the Dharwars of Mysore, described by Pichamuthu (1967).

Chemical Factors.- It is now a well-established fact that different primary minerals reflect different depositional environments (see Castano and Garrels, 1950; Krumbein and Garrels, 1952; Huber and Garrels, 1953; James, 1954; Huber, 1958; Garrels, 1960). Some of the above mentioned workers suggested that the two chief controlling factors involved in the formation of iron minerals are oxidation potential (Eh) and the hydrogen ion concentration (pH). According to Krumbein and Garrels (1952), in a restricted geosynclinal environment like the present case, Eh may range from positive i.e., oxidizing, at the surface to strongly negative i.e., reducing at depth; the pH may show variation from mildly alkaline at or near the surface to neutral or slightly acidic at depth.

Castano and Garrels (1950), Krumbein and Garrels (1952) and Huber and Garrels (1953) constructed stability diagrams for pyrite, siderite and oxide (hematite) facies in a normal sea water system. The works of Krumbein and Garrels (1952,p.12 Fig.1) show that there is no overlapping of the stability field among those minerals. Later James (1954) established the silicate facies and magnetite subfacies within oxide facies. Huber (1958, p.133, Fig.4) also prepared stability diagram for hematite, magnetite, siderite, pyrite and iron sulphide showing their stability fields in a normal sea water system and concluded that magnetite and hematite might coexist when thermodynamic equilibrium is attained at 25°C.

In the present case, however, iron formations are composed

of only two primary iron minerals viz., hematite and magnetite. Hematite is rather infrequent while magnetite occurs in great abundance. The primary nature of hematite has been well-understood by ore-microscopic studies. But, as regards magnetite, some discussion is necessary here to determine its true nature although it is closely associated with primary hematite wherever the two minerals coexist. In the light of above facts and following the works of James (1954) and Huber (1958), it may be suggested that both the ferric and ferrous-ferric oxides were deposited simultaneously in such a deep water environment which was mildly oxidizing to mildly reducing. Their deposition in quiet and deep water condition is further corroborated by the fine and more or less even lamination of the iron formation (see Hotchkiss, 1919). Under such circumstances magnetite should also be a primary mineral and should have intimate association with primary hematite.

Origin of Magnetite

In general, there are two different views on the origin of magnetite in the iron formations. They are as follows :

1. Magnetite is either a primary precipitate or formed by diagenetic reduction of ferric hydroxide (see Edward, 1936; Brown, 1943; James, 1954; White, 1954; Friedman, 1954; Huber, 1958, 1959; Chaudhuri, 1962; Chatterjee, 1964).

2. Magnetite is the product of metamorphism and oxidation of earlier ferrous iron minerals viz., siderite and greenalite

(see Dunn, 1937; Tyler, 1949; Mann, 1953; Goodwin, 1956; Leberge, 1964; Yui, 1966).

Before discussing the problem of magnetite, some of the relevant features noted during the mineragraphic study of ores and petrographic study of iron formation of Bicholim and Sanquelim Goa, are reviewed hereunder :

1. Among the two primary minerals viz., magnetite (mostly altered to martite) and specular hematite, the former is the dominant mineral in the iron ores.

2. The pseudomorphs of hematite after magnetite (martite) and the so-called primary specular hematite bear no such textural relation from which their relative age or paragenetic relation could be ascertained. Straight boundary line seperates the two minerals wherever they are in contact.

3. The laminated ores are made up of alternating thin bands of magnetite and specular hematite with clearly defined boundaries between the adjacent bands or occasionally the contacts of the bands appear graditional due to intermixing of one with the other mineral.

4. The crystal aggregates of magnetite are fairly uniform in their shape and grain size, and are not generally complexly intergrown.

5. The iron formation is conspicuously free from any iron silicate or carbonate mineral.

Discussion.- High temperature magnetites were so commonly reported that it leads one to believe that all of them are of high temperature origin. Nevertheless, some low temperature magnetites are also not rare.

Brown (1943, p.137) showed possible chemical reactions involved in the formation of low temperature magnetite under neutral and supergene condition. He also suggested that magnetite can form only below the water table where a delicate and usually unstable balance exists between oxidizing and reducing condition in the presence of a suitable precipitant. White (1954) observed that much of the magnetite of the Biwabik iron formation of the Mesabi range was either primary or diagenetic. James (1954) also arrived at the same conclusion as above and considered magnetite as a primary mineral belonging to the oxide facies. Friedman (1954) pointed out that low temperature authigenic magnetite may be more common in occurrence than it was earlier believed. Spiroff (1938) demonstrated experimentally that magnetite could be formed at a low temperature and pressure. He observed that if alkali was added to a solution having equivalent amounts of ferrous and ferric salts, a brownish-black magnetic precipitate was obtained. The X-ray diffraction pattern of this precipitate was identical to that of magnetite from other sources. According to Weiser (1953, p.88)

> hydrous Fe_3O_4 rather than hydrous Fe_2O_3 can be obtained by oxidation of ferrous hydroxide in an alkaline medium, provided the rate of supply of oxygen is slow.

Huber (1958, p.133, Fig.4) prepared a stability diagram for the oxides, sulphides and carbonate of iron in which a magnetite field was also included. The position of magnetite in the stability diagram suggests that it is as much an important diagenetic mineral as hematite, siderite, pyrite etc., in sedimentary rocks.

Thus, it is obvious that magnetite may be formed in a low temperature and pressure, and under a particular set of physico-chemical environment. Therefore, the principal lines of reasoning in support of primary origin of the magnetite in the present case may be summarized as follows :

1. Evidence of transformation of magnetite into hematite was available directly from the mineralogical study, the reverse case was seen not even in a single instance.

2.. The existence of distinctly seperate laminations of magnetite and specular hematite arranged alternately in the same ore, indicates that their development is related to diagenesis and not to metamorphism. A reasonable explanation for the co - existence of the two primary minerals at the depositional stage may be due to lack of complete equilibrium at the time of their formation (see Huber, 1958, p.138). Moreover, it may also be assumed that the condition under which magnetite and specular hematite were formed was limiting. As a result, a slight fluctuation of chemical environment may cause sequential and alternate precipitation of magnetite and hematite.

3. Even if it be presumed that magnetites were metamorphic

then there should be some index mineral from which the grade of metamorphism of the magnetite-quartzite rock could be known. Petrological studies, however, failed to recognise any such index mineral. As such the actual grade of metamorphism of the iron formations were difficult to ascertain. But from the study of associated country rocks it was concluded that the area did not undergo metamorphism beyond the chlrorite-biotite zone of the greenschist facies, and most likely same was the case with the banded magnetite-quartzite rock. Accordingly, there is no justification to presume that the bulk of magnetite in the iron formation is a product of low grade metamorphism of the original iron sediments.

Thus, following the above discussion, the magnetites under investigation, were considered to be largely of primary origin although their association with an insignificant amount of magnetite of metamorphic origin was not ruled out.

ORE DEPOSITS

It was generally admitted that the Precambrian iron ore deposits of India and their many equivalents in other parts of the world were originally marine sedimentary deposits usually known as iron formations. Widespread enrichment by replacement of these ferruginous parent rocks was considered to be the major factor for the later development of various types of ore. The mechanism of enrichment in some cases was simply the removal of silica and in others, addition of ferric hydroxide after the

leaching of silica. The process and rate of enrichment on the other hand depended on several factors, viz., composition of the rocks and their textures, favourable structure; climate, temperature, nature and rate of flow of the solvent, etc..

The principal varieties of the iron ores recognised in the area under reference, are hard laminated, friable, and powdery ore. Their mode of occurrence, physical, chemical and mineralogical composition have already been dealt with in detail in the previous chapters.

Source of Solvent

There is a major controversy regarding the source and nature of the solvent which was mainly responsible for leaching of silica from the iron formations. Many believe that the source of the solvent was meteoric water which played a major role in leaching of silica and also in enriching the parent rock supergenetically, while others consider that the ascending hydrothermal solution caused enrichment of the iron formations and still others believe that both hydrothermal and meteoric waters were equally responsible for the concentration of ores in the iron formations.

Van Hise and Leith (1911), in their report on Lake Superior iron ore deposits, concluded that the iron ores were formed as a result of the enrichment of iron formation by the downward moving meteoric water which leached vast quantities of silica and oxidized ferrous iron to ferric state. Gruner (1926b) on the other hand challenged Van Hise and Leith's weathering theory

and suggested that the solution which oxidized the iron ores and leached silica was of hydrothermal origin. In a later paper Gruner (1932) called attention to the association of minerals like specular hematite, martite, chlorite, sericite, talc, etc., in the ores as indicative of hydrothermal activity. Among many others who supported the hydrothermal theory are Jubert (1952), Mann (1953), Jolliff (1955), Baily and Tyler (1960). Leith (1931) and Royce (1932), however, favoured weathering theory for Lake Superior deposits. Dorr II (1964) also expressed similar views for the iron ore deposits of Minas Gerais, Brazil.

Most of the Indian geologists, who have closely studied some of the iron ore deposits of the country, favoured the weathering theory (see Jones, 1934; Krishnan, 1952; Spencer and Percival, 1952; Ghosh et al., 1963). Dunn (1937, 1941), however, was of the opinion that early enrichment of the ores was brought about by hot water but later the cold meteoric water played a similar role to enrich the ores.

Based on several evidences available from the area under review the present worker is in favour of accepting the weathering theory in preference to the hydrothermal theory and holds the descending meteoric water largely responsible for changing the nature of the iron formations and leading to the concentration of the iron ores. The following are the main reasons in support of the above mentioned view of the author :

1. The absence of any large body of intrusive or extrusive rocks in the neighbourhood of the ore bodies failed to account

for any connection between the solvent and the igneous source.

2. The deposits are near-surface and no good deposit was so far reported from below the present ground water level.

3. Occasional association of scattered and partially leached fragments of iron formation within the iron ores at depths.

4. Iron silicate minerals are completely absent and the mineralogy of the ores is simple. Also, the increasing proportion of ferrous oxides and correspondingly decreasing proportion of hydrated ferric oxide and aluminia from surface to depths indicate their formation under normal oxidizing or lateritic weathering condition, rather than due to any ascending solvent.

5. Textural evidence indicates partial replacement of the earlier magnetite-martite ores as well as filling of their intergranular spaces by supergenic goethite.

Residual Concentration and Enrichment

Most of the workers dealing with the genesis of iron ores agree that residual concentration and secondary enrichment of the iron formation are the most effective processes of ore formation. Widespread leaching of silica may cause complete disaggregation of the iron formation resulting residual concentration while the process of secondary enrichment enriches further the residually concentrated ores by the addition of iron mostly in the form of ferric hydroxide. Silica, which occur

generally in the form of medium to fine-grained quartz, is much more soluble than iron in meteoric water . Siever (1962) has shown that solubility of silica in water at a temperature of 25°C was about 10 parts per million. Reed et al. (1963) also believed that considerable amount of quartz might be taken into solution from the quartzite in a cool climate. This fact is in close agreement with the observations made by Ruckmick (1963) in the iron ore district of Cerro Bolivar, Venezuela. His analysis of the spring waters from iron formation showed that the average mobility of quartz in spring water was 10.5 ppm. Unfortunately, no such data is available from any iron ore province of India.

Physiography, climate and grain size are a few important factors which facilitate leaching of silica. A shield area which attained a crustal stability over a long time is supposed to be a favourable condition for the development of mature topography and deep weathering. Under such a condition and specially, in a humid and tropical climate with high seasonal rainfall, silica particularly, fine to medium-grained, may be removed in solution from a great depth of about 100 meters or even more when the structure, grain-size and texture of the parent rock are favourable. James (1955, p.1480) has emphasized the role of grain-size in the development of soft iron ores in Northern Michigan. He observed that in the lower zone of metamorphism (chlorite-biotite), where grain-size of quartz was relatively small, silica have been leached and thus the principal soft ore deposit was restricted to the lower zone of metamorphism. The low-grade

of metamorphism of the country rock and smaller size of the quartz grains in the iron formations of the investigated area is perfectly consistent with the foregoing conclusion drawn by James (1955).

Silica, once dissolved by supergene solution, is insensitive to Eh and pH changes and therefore, it will not precipitate easily. Instead, it will be carried out of the system by the surface and ground waters. This process is the paramount factor responsible for leaching of silica from the iron formations.

During the leaching of silica some iron, though far smaller in quantity than silica, may also be dissolved by the circulating meteoric water. Some suggested that organic acids facilitated the increasing solubility of iron (see Guild, 1957; Park, Jr., 1959). The role of carbon dioxide in increasing the solubility of iron was advocated by Hem (1960), Oburn and Hem (1961). They thought that various microrganisms played some role in the solution and transportation of iron since their presence in the soil reduces Eh and pH of the solvent.

Whatever may be the actual cause, iron is generally leached as ferrous ion (Fe^{++}) or ferrous hydroxide $Fe(OH)_2$ aided by acidic solution. With a good supply of oxygen iron readily oxidises and precipitates as ferric ion (Fe^{+++}) or ferric hydroxide $Fe(OH)_3$ under alkaline condition at a pH value of above 7.0 (see Dutta and Nandy, 1964, p.107). Obviously, such a favourable condition prevailed more near the surface than at depth. Thus, iron taken into solution may either be redeposited

at least partly as limonite or entirely removed from the system since it could be transported by the solution so long its Eh and pH remain unchanged. In such a system the net loss of iron should be much less than silica (see Dorr II, 1964, p.1225-1226).

The above-mentioned mechanism seems to be the primary cause of secondary enrichment of residually concentrated ores. The source of iron in the solution responsible for secondary enrichment was thus the iron formation itself. The solution containing iron moves to the surface by the capillary action or ephemeral springs and seeps and thus comes in greater contact with air. As a result, Eh of the solution increases and the ferrous iron oxidises to an insoluble ferric hydroxide or limonite. Hem: and Cropper (1959, p.16) described the process as follows :

> Water below the land surface and not in contact with air probably has Eh values of 0.20 volts or less and a relatively low pH (less than 6) if enough excess carbon dioxide is present. Under these conditions, ferrous solution as high as 50 ppm are permanently stable. As the water approaches the surface of the ground and dissolves oxygen from the air, (a) nonequilibrium situation.... sets in. Water low in Eh and high in Fe^{++} is continually supplied. Ferrous-iron oxygenation and ferric-hydroxide precipitation both continue.

The other process, which is likely to promote deposition of limonite, is the evaporation of iron-rich solution brought to the surface by ephemeral springs and seeps. Between showers in the rainy season and early part of the dry season, soiless slopes are moistened locally and continuously remain wet by water seeping from the surface. Iron, transported in a colloidal state or in solution in a ferric state may be deposited through

evaporation of the solution (see Dorr II, 1964, p.1234).

Thus oxygenation of ferrous iron and evaporation of ferric iron are the most effective processes which may cause deposition of limonite in the hard laminated iron ores as well as in the true laterites.

Type of Ores

It may be recalled here that the near-surface hard and laminated iron ores of Bicholim and Sanquelim grade downward into a zone of powdery ore through an intermediate zone of friable ore. Although these ore zones are graditional and fairly persistent throughout the area yet they do not have uniform thickness and continuity downwards due to occasional intervention of the country rocks or lean ore mixed with ochre or clay.

The development of these three types of ore is not only interseting but also have great economic significance. As has already been mentioned earlier that the iron ore deposits were formed by the process of weathering, leaching, oxidation and enrichment of the iron formations by the circulation of meteoric water through them under a favourable climatic condition.

The probable processes responsible for oxidation and supergene enrichment of the iron formation and its conversion into three major types are presented below.

Hard Laminated Ore.- The hard laminated ore, which commonly occurs near the surface and usually under a capping of ferruginous laterite of variable thickness, often preserved the bedding

lamination of the original iron formation. Irregular masses of iron ore laterite occurring between the overlying ferruginous laterite and underlying hard laminated ore, also have some fragments of partially lateritized laminated hard ore. All these intergraditional features from ferruginous laterite, through iron ore laterite to hard laminated ore strongly suggest that the same supergene process was responsible for the large - scale lateritization of the protore as well as oxidation and residual concentration of iron ores along certain zones. The prime cause of lateritization and supergene enrichment of the ores was, therefore, the leaching of silica from the parent rock followed by the precipitation of ferric hydroxide in the void spaces from meteoric water circulating through the rock.

The extent of desilicification and enrichment on the other hand was controlled by several factors like structure, texture, grain-size, etc., of the protore and the nature of attacking solvent. Under the influence of humid and tropical climate with a high seasonal rainfall, as in the territory of Goa, the fine-grained silica in the protore concerned has a greater chance of being taken into solution by meteoric water. Since the precipitation of dissolved silica as well as its rate of solibility does not depend much on Eh and pH changes, silica of the protore, once dissolved by meteoric water, will not precipitate in the system. Further, in addition to the grain-size of silica, such favourable structural features as bedding lamination, high angle of dip, etc., facilitated flow of this meteoric water out from

the iron formation. This long and continued process of solution and removal of silica from the protore by ground water on an extensive scale was held responsible for the residual concentration of ores in the iron formation. Concurrently, with the leaching of silica also some iron are likely to be leached out from the protore as ferrous hydroxide because of the acidic property of the meteoric water. Thus iron, once dissolved, is not likely to precipitate so long as the Eh and pH of the iron solution remain unchanged. But it may be redeposited as ferric hydroxide either due to oxidation or evaporation of the solvent. Both oxidation and evaporation are obviously ideal at the near-surface atmospheric condition than at depths. Accordingly, iron hydroxide in the form of goethite is likely to be deposited in greater quantities in the residual ores occurring close to the surface.

Mineralogical and textural study of the hard and laminated ores shows that they have goethite in abundance. Polished sections of the ores further show that goethite occupies most of the intergranular spaces in the magnetite-martite ore, which were once occupied by silica. This gives a clear indication that goethite was introduced in the system from without subsequent to the removal of silica. Largely, due to infiltration of colloidal hydroxide of iron in the available pore spaces and other structural planes the residual ores near the surface were not only enriched but also made hard and compact.

Formation of manganiferous iron ores is akin to that of

hard iron ores except that pyrolusite and psilomelane, instead of goethite, were introduced in a similar manner in these ores.

From the above considerations it is evident that the hard ores had originated essentially as a result of residual concentration and supergene enrichment of the near-surface protore. The former process was mainly responsible for almost thorough leaching of silica and residual concentration of iron in the protores and the latter, for enriching the protore with the addition of goethite. It is, therefore, expected that the concentration of iron in the hard ores should be highest, since in the friable ore secondary enrichment is only partial and in the powdery ore, it is minimum, as will be discussed later. But the results of chemical analyses of all these ores show iron concentration in the reverse order. A plausible explanation for the lower value of iron in the hard ore is due to the fact that it has the highest concentration of goethite which is about 60 $^{o}/_{o}$ of the total iron minerals. It is, therefore, obvious that with increasing proportion of goethite, the grade of the ore should go down considerably under supergene condition of enrichment. On similar grounds greater values of iron in the friable and powdery ores may be attributed to decreasing proportion of goethite from the friable to the powdery ores with corresponding increase in magnetite and hematite.

Friable Ore.- A gradual passage of the near surface hard laminated ore into a lower friable and porous ore zone was characteristically observed in several mine sections. Formation of these friable ores was at least partly similar to that of hard

laminated ores in a sense that the protores have also been relieved of silica by the leaching action of meteoric water below the upper hard ore zone. But unlike the hard ores, there was little infiltration of goethite in the intergranular spaces of the residually concentrated protore due to which they remained friable and porous since their desilicification. The porosity of the ores was largely due to the micro-voids created as a result of removal of silica in solution from the system. During it downward journey, the iron-laden meteroric water after depositing bulk of its iron hydroxide in the uper hard ore zone, is likely to lose much of its acidic property. When such a weakly acidic solvent moves further down its capacity to remove silica from the system, however, continues to remain unchanged although the solvent loses much of its capacity to dissolve iron on a large scale. As such, the solution will continue to remain undersaturated in iron hydroxides with increasing depth from the surface. Therefore, as compared to the overlying hard ore zone, the deposition of iron hydroxide in the friable or in the lower powdery zone will be gradually restricted.

The above facts may reasonably account not only for the restricted concentration of goethite but also for the porosity and deficiency of silica in the friable ores.

Powdery Ore.- With increasing depth, the friable ore grades into an unconsolidated powdery ore or 'blue dust'. The mineralized meteroic water, while moving down from the surface

would discharge bulk of its iron content in the hard and the remaining in friable ore zones. The solvent which moves further down below the two zones would become neutral and almost free from iron on account of which neither any more iron will be dissolved from the protore nor precipitated from the solvent, but it would still be capable of dissolving and removing silica from the iron formations. The solvent would thus completely leach silica from the protore without depositing much hydroxide of iron in this powedery zone.

The insignificant presence of goethite in the magnetite-martite rich powdery ore is a strong evidence in support of the process of leaching and residual concentration described above.

From the nature of the deposit and its mode of formation, discussed above, it is apparent that the iron formation of the area have contributed much of the iron ores through their residual concentration and supergene enrichment influenced by such congenial climatic condition which favoured chemical decay of the protores since their formation in the Precambrian times.

SUMMARY AND CONCLUSIONS

About a couple of years after the liberation of Goa from Portugese occupation in 1961, the author started a systematic geological investigation of one of its largest iron ore deposits at Bicholim taluka, in the northern part of Goa, in which Sirigao-Bicholim and Sanquelim are the two important localities having rich deposits of iron ores. Although it was chiefly aimed at the structural and genetic studies of the ore deposits yet considerable attention was paid to deal with their stratigraphy, mineralogy and some important economic aspects. A summary of this study as well as several interesting conclusions arrived at, are given in the following paragraphs.

1. The iron ore deposits of Bicholim are confined to the Precambrian phyllites of North Goa, which are in many respects similar to the well-known Precambrian Dharwar schists of Mysore. Phyllites and banded ferruginous quartzite are the two major rock types in the area under investigation. These banded ferruginous rocks are believed to be the source rock of iron ore deposits and hence, they are treated here as iron formations. The phyllites have also some small lenses of massive quartzites which crop out sporadically in the area. There are a number of basic dykes intruding into the schistose formations of the area. They have a general NNW-SSE to NW-SE trend. Widespread

lateritization have greatly obliterated the true nature of all the rock outcrops except of the basic dykes, which can be easily recognised in the field. On the basis of field survey and mapping, an attempt was made to build up the stratigraphic sequence of the area as follows :

	Recent	.....	Alluvium
	Sub-recent	.....	Laterite
	Deccan Trap?	.....	Dolerite
Precambrian	Intrusive	.....	Metadolerite
	Schistose formation	.....	Phyllites with banded ferruginous quartzites and some massive quartzites.

The lithological characters and some primary sedimentary structures of the phyllites and banded ferruginous quartzites show that they are low grade metasedimentary rocks.

The strike of the schistose rocks is NW-SE, which is more or less the same as that of the Dharwars of the type area in Mysore. They generally dip northeastwards. Structurally, the area occupies a part of the western limb of a northwesterly plunging regional syncline, the axis of which passes through Zormen, Querim, etc., which fall beyond the area investigated. Both Sirigao-Bicholim and Sanquelim outcrops of the banded ferruginous quartzites represent two northwesterly plunging and northeasterly dipping isoclinal anticlines. The former

anticline was further cross-folded due to a drag. The structure and relative position of two anticlines indicate that they are left-handed en echelon folds.

On the basis of their lithology, comparable grade of metamorphism, structural similarity and association of iron ores, the schistose rocks of the area have been correlated with the Middle Dharwars of Northern Mysore.

2. The petro-mineralogical studies of the phyllites confirm the fact that their grade of metamorphism is considerably low and equivalent to the chlorite zone of the greenschist facies. In the absence of iron or any other silicate mineral/the metamorphic grade of the ferruginous quartzite also appears to be low. Some of the basic dykes in which the mineral assemblages are somewhat metamorphosed and show preferred orientation, are identified as metadolerites and considered as the older Precambrian intrusives. The younger ones having unaltered pyroxene, plagioclase felspars and olivine may be of the Deccan trap age.

3. The iron ore deposits of Bicholim are mainly confined to the two well-defined ridges, one of which extends from Sirigao to Bicholim and the other occurs near Sanquelim. The iron ores are usually capped by ferruginous laterite and iron ore laterite which more or less grade downwards into the former imperceptibly. The laterites, however, have no economic importance. The bulk of the commercial grade of ores are mined

from the ore lying below the laterite overburden. The ore horizon has been divided into three zones viz., hard, friable and powdery, which can be easily recognised by their nature and physical characters. The hard ore zone, which occurs in the upper part of the deposits gradually passes downwards into a zone of friable ore which in turn becomes powdery further down. Occasionally the hard ores are associated with some manganese ores such as pyrolusite and psilomelane and this variety of iron ore is known locally as ferro-manganese. There are also some small but rich pockets of manganese ores which are occasionally found in the overlying ferruginous laterites.

Analytical results of the iron ores show that the average iron contents in the hard, friable and powdery ores are 62 °/o , 64 °/o and 65 °/o respectively. It is very interesting to note that Fe_2O_3 , FeO and SiO_2 contents gradually increase from the hard to powdery ore while Al_2O_3 and combined water go on decreasing. Mineralogical composition of these ores also show that the quantity of goethite decreases significantly from the hard through friable to powdery ore with a corresponding increase of hematite and magnetite. All these facts regarding the nature and composition of the different types of ore and their field relations indicate that they were largely influenced by several complex supergenic processes in which meteoric water played a dominant role.

An attempt was also made to classify the ore deposits into four types viz., hard, friable, powdery and lateritized ores on the basis of their physical characters, mineralogy and chemical composition.

Economically, the iron ore deposits of Goa and particularly of its northern part, which contribute approximately 75 °/o of the territory's total annual production of iron ores, have a great promise. According to a recent estimate, made by the Geological Survey of India, Goa has a reserve of about 405 million tonnesof iron ores, which include about 94 million tonnes of hard (52 °/o Fe) and about 311 million tonnes of friable and powdery ores (62 °/o Fe). According to the same source, the combined reserves of Bicholim and Sanquelim deposits are about 98 million tons. On account of the locations of most of the important deposits of Goa within a radius of about 30 km from the nearest ports and also excellent waterways for easy inland transportation, the f.o.b of its iron ores is cheap and this may be the main reason as to why the ores are in great demand in several foreign steel-producing countries such as Japan, West Germany, Italy, etc.. Since the iron ores of Goa have been fast attracting the international interest, it is now very necessary to have a stricter quality control than before and also to install another agglomeration plant somewhere near Bicholim town. Moreover, because of the rapid depletion of lumpy ore and the problem of marketing the blue dust and iron ore fines, some important suggestions are given for controlling

the quality of the ores and also for improving the economy of this important iron-rich territory of India through modernizing mining operations and proper utilization of its iron resources.

4. Structurally, the Sirigao-Bicholim deposit forms a northwesterly plunging and somewhat overturned isoclinal anticline whose axial trend is NW-SE. The northwestern part of this anticline near Sirigao has been cross-folded into a smaller syncline and a corresponding anticline. The trend of the axes of the cross-folds is NNW- SSE, which makes an angle of about 15° north of the general axial trend of the Sirigao-Bicholim anticline.

The smaller Redeval deposit, which occurs about 400 meters northeast of the southeastern part of the Sirigao-Bicholim deposit also have a general northeasterly dip and NW-SE strike. On the basis of its structure, absence of any fault valley between this and the adjacent Bicholim deposit, and also of its great physical and mineralogical resemblences with the other ores of Bicholim it is logical to believe that the Redeval outcrop represents the northeastern limb of the much eroded anticline whose other limb form the Sirigao-Bicholim deposit.

The Sanquelim deposit reveals that it is also a case of isoclinally folded anticline plunging northwestwards and that

its limbs dip northeastwards. The axial trend of the anticline is NW-SE. Due to removal of a greater part of the anticline by erosion its outcrop pattern became V-shaped.

There are also several important evidences to believe that both the primary and secondary structures of the iron formations have made the [illegible] flow and circulation of the metoric water through them easier and due to which the processes of residual concentration and supergene enrichment of the iron ores were very much effective.

5. Mineragraphic study of the iron and the associated manganese ores led to the identification of specular hematite, magnetite, martite and goethite among the iron minerals, and pyrolusite and psilomelane among the manganese minerals. Some of the iron ores developed schistosity due to preferred orientation of the specular variety of hematite and some magnetite, which are generally segregated in alternate bands. The primary nature of the two minerals has been amply justified by their straight boundary relation and the complete absence of any replacement relation and hence, both magnetite and specular hematite are considered to be the earliest of all the iron minerals to appear and contemporaneous in time sequence. Among the supergene iron minerals, the time range of the second generation of hematite, which is actually a pseudomorph of martite after magnetite, is more or less overlapping with that of the goethite, which occurs as pseudomorph after magnetite. There is also another generation of supergene hematite, which

is actually a pseudomorph after goethite. It has overlapping time relation with the second generation of colloform or massive goethite, which is usually a dominant mineral in the hard ores.

Lepidocrocite occurs rather insignificantly in close association with the colloform goethite with which it has an overlapping time relation. Both pyrolusite and psilomelane, associated with the iron ores, are late supergene minerals.

6. Largely guided by the different views regarding the origin of iron formations and the types of ore associated with them and based on the author's own field and laboratory investigations, the genesis of the iron ores of Bicholim is summarised as follows :

i) Weathering and erosion of ancient land masses supplied so much of iron and silica that they served as the primary source of iron formations. Probably iron was transported in solution and precipitated in a ferrous-ferric or ferrous state while silica was deposited in a colloidal state.

ii) Banding in iron formations was due to rhythmic chemical precipation of iron and silica in the Precambrian basin of deposition under a particular set of physico-chemical condition which never repeated in later geological periods.

iii) Probably a restricted marine environment like that of the Dharwar geosynclinal phase was ideally suitable for the

deposition of iron formations during the period concerned.

iv) As most of the magnetites and specular hematites in the iron formations are primary, they should be considered as belonging to the oxide facies of James (1954). A mildly oxidizing to mildly reducing deep water environment was envisaged for the deposition of these primary iron minerals.

v) The solvent responsible for the mass leaching of silica from the protores, was meteoric and subsurface water and not derived from any hydrothermal source.

vi) Mass residual leaching of silica, oxidation of magnetite to hematite and deposition of some iron hydroxide under certain favourable physiographic, structural and physico-chemical conditions were the most important processes involved in the transformation of the iron formations into hard, friable and powdery iron ores.

vii) The hard ores owe their origin to almost complete removal of silica by leaching from the near-surface protores and the subsequent deposition of goethite in it from the solutions circulating through the intergranular void spaces. On the other hand the protores, occurring at some depth below the surface, were much disaggregated and rendered powdery because of certain physico-chemical conditions under which the meteoric water continued to leach silica but without being able to deposit any more

goethite at such a depth. In the case of friable ore, which occur between the hard and powdery ore zone there was a complete leaching of silica but due to inadequate supply of goethite, many of the void intergranular spaces in the leached iron formations could not be filled up. This is the cause of the protores remaining porous and friable just below the hard ore and above the powdery ore zone.

It may now be concluded that at an earlier stage the residual concentration of magnetites occured at all levels in the iron formations due to complete leaching of silica. But the subsequent or even contemporaneous supergene oxidation of magnetite into hematite and their secondary enrichment with the addition of colloform or massive goethite were most effective in the upper part of the deposit and as a result of which it gave rise to an upper zone of hard and enriched ores consisting dominantly of hematite and goethite.

On the contrary, there was practically no secondary enrichment and a very restricted oxidation of the underlying zone of powdery ores due to which they were left completely loose and thus retained their original state as well as mineral composition. Between the upper hard and the lower powdery ore zones, obviously there should be a transition zone in which the ores would be neither hard nor powdery but friable, and also have small amounts of magnetite and goethite on account of restricted oxidation and enrichment.

The residual concentration and secondary enrichment of the protores, being extremely slow supergenic processes and largely dependent upon the past topographic and climatic conditions of the area, had more likely continued through several geological periods rather than remaining confined to a single one.

EXPLANATION OF PLATES

PLATE-I

fig. 1 A thinly laminated banded ferruginous quartzite usually associated with iron ore deposits of Bicholim, Goa. 1/2 Nat.size.

fig. 2 A rare variety of thickly banded ferruginous quartzite consisting of alternate bands of silica (white) and iron oxides (dark grey). 1/2 Nat.size.

fig. 3 A handspecimen of medium grained and unmetamorphosed basic dyke. 1/2 Nat.size.

fig. 4 Pisolites in aluminous laterite derived from phyllites. 2/3 Nat.size.

PLATE-II

fig. 1 Schistosity in chlorite phyllite developed due to preferred orientation of quartz and felsper grains (white) and flaky micas. X32 Plane polarized light.

fig. 2 Fractured and rounded to subrounded porphyroblasts of quartz, micas and chlorite being bendaround them. X90 crossed Nicol.

fig. 3 Local occurrence of interlocking aggregates of quartz in chlorite phyllite. Also note the twinning in the porphyroblast of albite in the centre of the photomicrograph. X90 crossed Nicol.

fig. 4 Untwinned sieved felspar containing innumerable minute inclusions of flaky minerals. X90 crossed Nicol.

PLATE III

fig. 1 Segregated band formed by flaky minerals (white). X32 crossed Nicol.

fig. 2 Coarse-grained calcite in calcareous phyllite having some felspar and quartz porphyroblasts. X90 crossed Nicol.

fig. 3 Porphyroblasts of twinned albite in calcareous phyllite riddled with minute inclusions of apatite, chlorite, sericite, etc. X90 crossed Nicol.

fig. 4 Well-developed schistosity in calcareous phyllite, biotite flakes (dark) stretched along schistosity direction. X140 Plane polarized light.

PLATE IV

fig. 1 Alternate dark ferruginous and light siliceous bands in banded ferruginous quartzite. X32 Plane polarized light.

fig. 2 Siliceous bands in ferruginous quartzite having little iron oxides, the proportion of which gradually increases as the ferruginous band approaches. X90 Plane polarized light.

fig. 3 Cherty quartz in siliceous band of ferruginous quartz. X32 crossed Nicol.

fig. 4 Quartz showing mosaic texture. X90 Plane polarized light.

PLATE V

fig. 1 Partial replacement of quartz crystals by iron oxide (black) mostly along their grain boundaries. X60 Plane polarized light.

fig. 2 Subhedral to enhedral crystals of magnetite (black) in the ferruginous band with subordinate amount of quartz (white). Note also the fairly uniform size of the magnetite crystals. X32 Plane polarized light.

fig. 3 Crude schistosity marked by the orientation of specular hematite (black). X90 Plane polarised light.

fig. 4 Granoblastic texture in metadolerite. X32 crossed Nicol.

PLATE VI

fig. 1 Blastophitic texture in metadolerite, plagioclase laths are enclosed in altered pyroxene. X90 crossed Nicol.

fig. 2 Altered plagioclase having inclusions of epidote and zoisite. X90 crossed Nicol.

fig. 3 Actinolite, uralite and chlorite along the crystal boundary of hornblende (left hand corner). Note clusters of epidote grains in the upper part of the photomicrograph. X90 crossed Nicol.

fig. 4 Characteristic ophitic texture in dolerite. X32 crossed Nicol.

PLATE VII

fig. 1 Clouding of plagioclase due to its partial alteration. X32 crossed Nicol.

fig. 2 Olivine altering into sepentine along grain boundaries and fracture planes heaving relicts of former. X32 Plane polarized light.

fig. 3 A portion of the 35 meter level face of hard ore (right hand side) workings at Sirigao mines. Left hand side of the photograph is a ferruginous laterite capping over hard ores.

PLATE VIII

fig. 1 A close-up view of the steeply dipping, and thinly laminated friable ore at Sanquelim mines.

fig. 2 Highly dipping transitional zone of friable ore (left hand side) and powdery ore (right hand side) in the Sanquelim mines. Note the thin laminations and minor folds in the undisturbed face of powdery ore.

PLATE IX

fig. 1 A general view of a part of the Coplegaichem concessions at Sirigao showing mining of powdery ore in progress at 15 meter level.

fig. 2 A handspecimen of hard ore showing fine laminations. 3/2 Nat.size.

fig. 3 A handspecimen of folded hard ore. Individual laminae are more distinctly shown by voids left after leaching of silica. 1/2 Nat.size.

PLATE X

fig. 1 Ground surface of a handspecimen of ferro-manganese ore with fine laminations parallel to the given scale. 1/2 Nat.size.

fig. 2 A handspecimen of iron ore laterite showing pisolites in the upper part and crude lamination in the lower part. 4/3 Nat.size.

fig. 3 Subhedral to enhedral crystals of martite without any relict of magnetite. X160 Oil immersion.

fig. 4 Specular hematite with intervening goethite or gangue. X730 Oil immersion.

PLATE XI

fig. 1 Subhedral crystals of magnetite. The intergranular dark spaces are occupied by gangues. X160 Oil immersion.

fig. 2 Lepidocrocite (white, around the dark vug) surrounded by gangue (dark grey). The light grey goethite is around the gangue. X160 Oil immersion.

fig. 3 Atoll structure formed due to complete enclosure of goethite (grey) by lepidocrocite (greyish white). X160 Oil immersion.

fig. 4 Subhedral grains of pyrolusite in the upper part of the figure exhibit mosaic texture and below are the accicular crystals of pyrolusite. X35.

PLATE XII

fig. 1 Banded structure shown by magnetite-martite (white) and gangue (dark) occurring in alternate bands. X35.

fig. 2 Thin trains of goethite (grey) and gangue (dark) along the bedding planes exhibit banded structure. X35.

fig. 3 Granular texture in a hard iron ore, goethite (dark grey) occupying the intergranular spaces of martite (grey white). X160 Oil immersion.

fig. 4 Granular texture in manganiferrous iron ore. Grains of martite and magnetite are surrounded by pyrolusite (grey white). X160 Oil immersion.

PLATE XIII

fig. 1 Granular texture shown by martite in a protore in which silica (dark) occupies the intergranular spaces. X160.

fig. 2 Preferred orientation shown by specular hematite in a schistose ore. X90.

fig. 3 Crude schistosity is developed due to imperfect preferred orientation of magnetite or martite crystals. X50.

fig. 4 Colloform texture with alternate concentric bands of pyrolusite (grey) and gangue (dark). X50.

PLATE XIV

fig. 1 Concentric rings of psilomelane (white) and pyrolusite (dark grey). Ore or gangue is present at the centre of the colloform rings. X35.

fig. 2 Subhedral and radiating pyrolusite crystals occur in a vuge of manganese ore. Note also shrinkage cracks perpendicular to the surface of colloform ore in the upper left and lower right side of the figure. X35.

fig. 3 Incomplete pseudomorphic replacement of magnetite by martite is indicated by the presence of some relicts of magnetite (slaty grey). X730 Oil immersion.

fig. 4 Pseudomorphic replacement of magnetite by goethite (dark grey) leaving some relicts of the former(light grey). There is also an indication of later replacement of goethite by hematite (white) along the margin of the pseudomorphs. X160.

PLATE XV

fig. 1 Initial replacement of magnetite(pale grey) by martite (white) along grain boundaries of the former. X160 Oil immersion.

fig. 2 Wedmanstetten like texture due to pseudomorphic replacement of magnetite by martite following octahedral cleavage partings of the former. X730 Oil immersion.

fig. 3 Partial replacement of a cubic magnetite crystal(white) by martite along its grain boundaries. The other crystals show complete alteration into martite. X160 Oil immersion.

fig. 4 Straight boundary relation between a euhedral crystal of magnetite (dark grey) and several specular crystals of hematite (white) surrounding the former. X730 Oil immersion.

PLATE XVI

fig. 1 Parts of the grain boundary of a martite crystal (white) is being irregularly replaced by goethite (grey). X730 Oil immersion.

fig. 2 Goethite pseudomorphs after magnetite. It was subsequently replaced by hematite (white) leaving some relicts of the former (light grey). Intergranular space material (darker grey) is also goethite. X160 Oil immersion.

fig. 3 Wedmanstetten like replacement texture shown by having innumerable hematite plates (white) along the octahedral cleavage of the original magnetite. X730 Oil immersion.

fig. 4 Irregular rim replacement of goethite (dark grey) by martite (white) showing that the replacement is in progress. X160 Oil immersion.

PLATE XVII

fig. 1 The biggest pseudomorph of martite (white) after goethite is sometimes being marginally replaced by goethite (dark grey) encroaching from the intergranular spaces. Note also some small relicts of goethite (light grey) in the martite. X160 Oil immersion.

fig. 2 Colloform psilomelane (white) and pyrolusite (light grey) in the intergranular spaces of martite (dark grey) in manganiferrous iron ores. X160 Oil immersion.

fig. 3 Irregular marginal replacement of largely martitised magnetite crystal by colloform psilomelane and pyrolusite. Note the advancement of two different

processes of replacement due to which the crystal boundaries of magnetite (light grey) and martite (dark grey) do not match.X730 Oil immersion.

fig.4 Concentric bands of colloform goethite (dark grey), psilomelane (white) and pyrolusite (light grey) in manganiferous iron ore . X160 Oil immersion.

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Personal Vitae

A. K. Majumdar

I happen to belong to an enlightened Indian Hindu family and hail from that part of undivided Bengal, which now constitutes the Eastern wing of Pakistan. My father, Dr. U.K.Majumdar, after serving as a medical officer for more than thirty years in a remote Tea garden concern in upper Assam, has recently settled down at Barrackpore, a sub-divisional town in the State of West Bengal, India.

I had my early education at Dibrugarh, Assam and later on, moved to Aligarh for securing my B.Sc. and M.Sc., degrees from the Aligarh Muslim University. Being greatly inspired by my father's long cherished desire to see one of his two sons going for advanced studies, I decided to join research at the Aligarh Muslim University, Aligarh, shortly after receiving my M.Sc. degree.

I have the pleasure to acknowledge the moral strength and support which I received from my wife, Mrs. Namita Majumdar, who played an important role during the accomplishment of this work.

I feel a deep sense of gratitude to my father and of thankfulness to my wife for their good wishes at the completion of this project. I also avail of this opportunity to dedicate the thesis to my revered father, who has been a strong source of inspiration to me since my childhood.

PLATE. I

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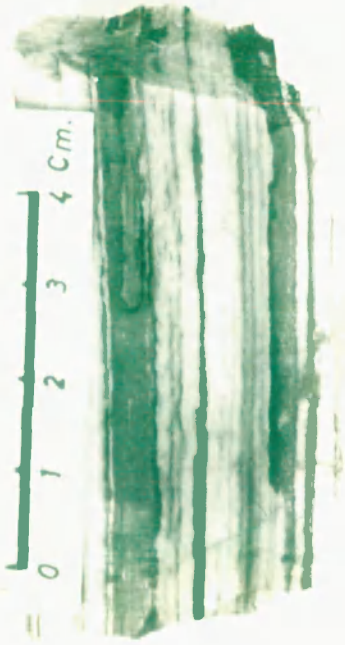

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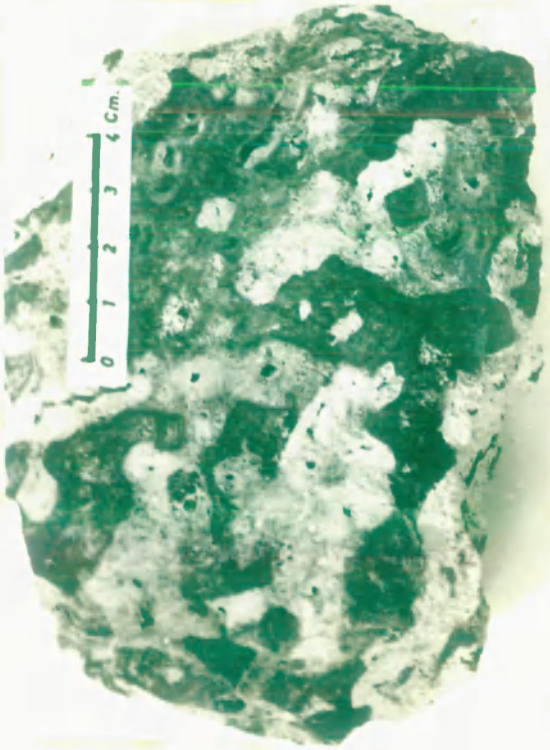

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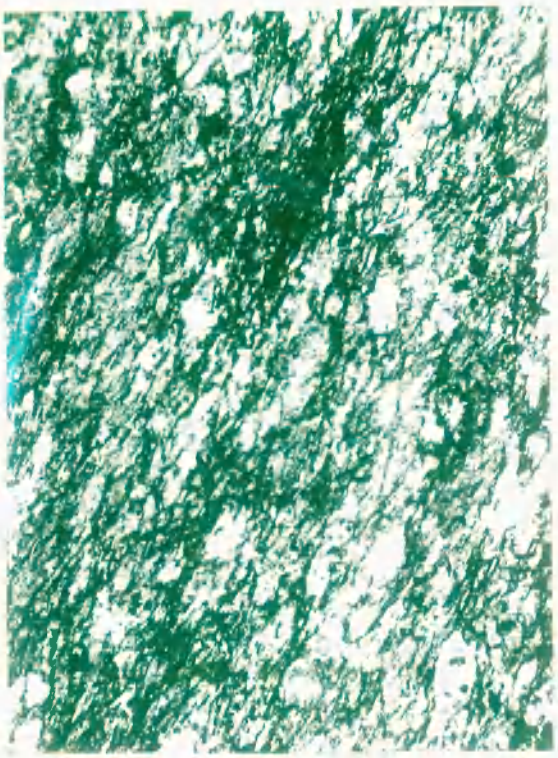

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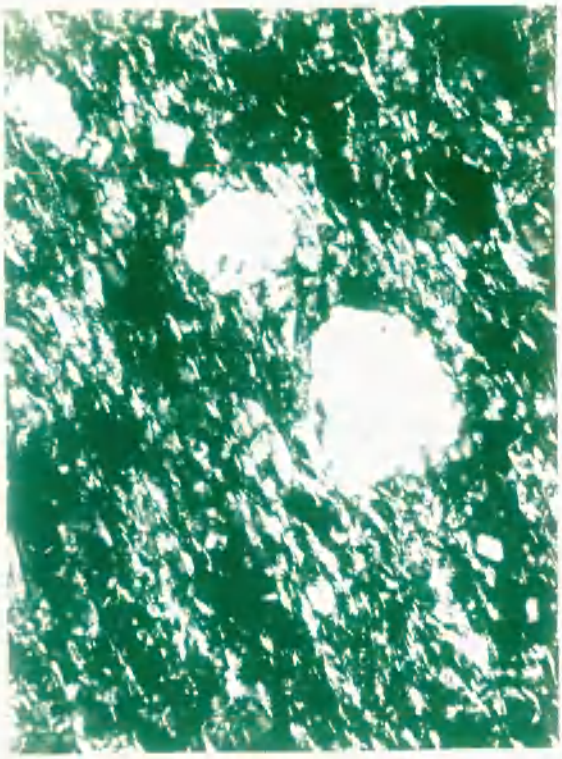

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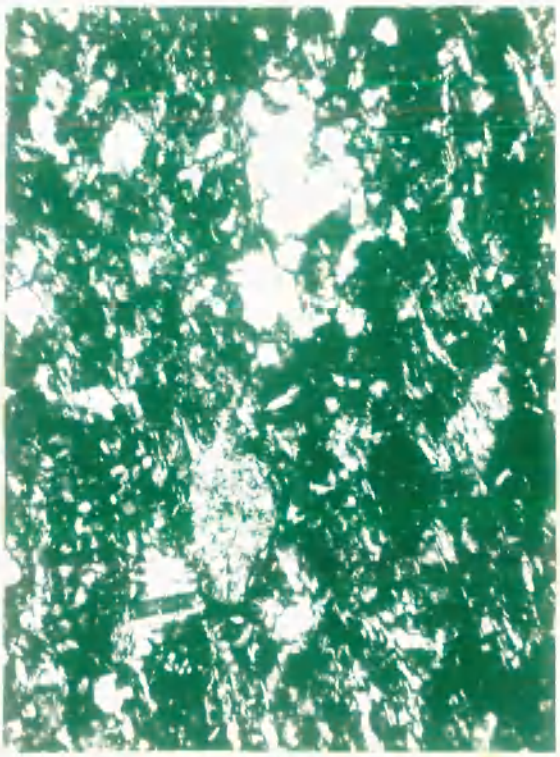

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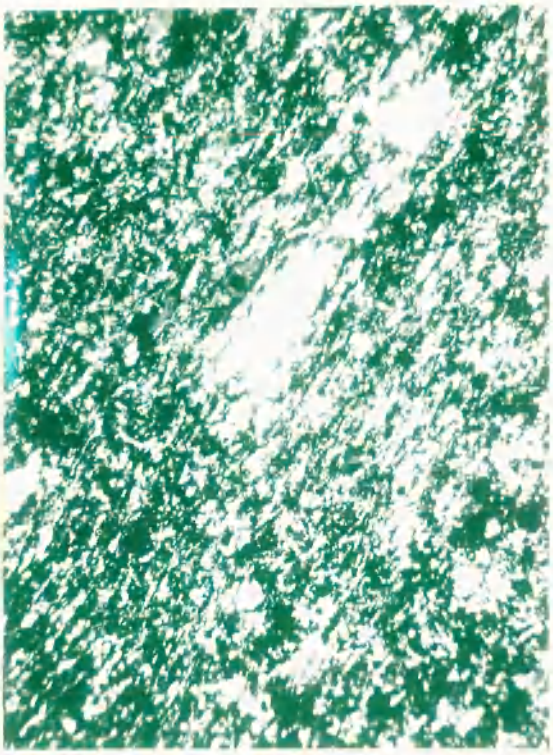

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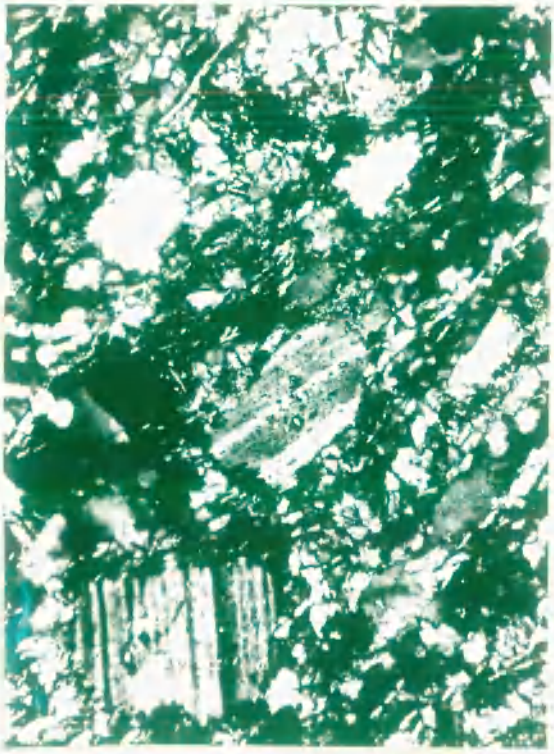

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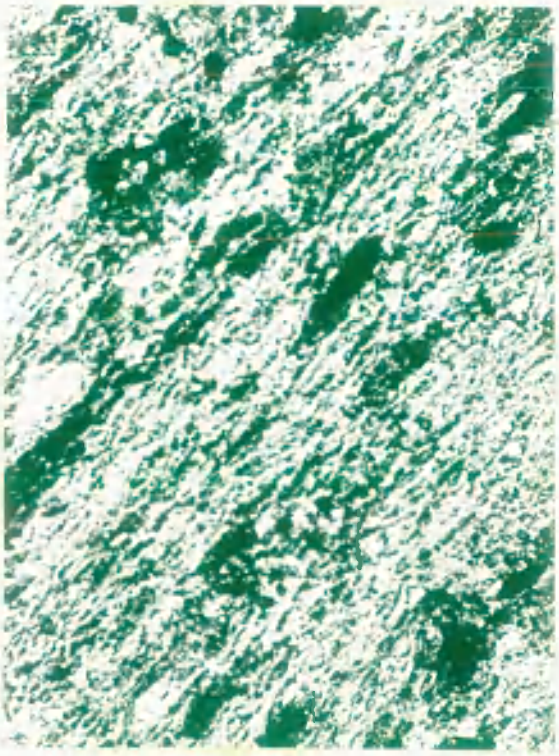

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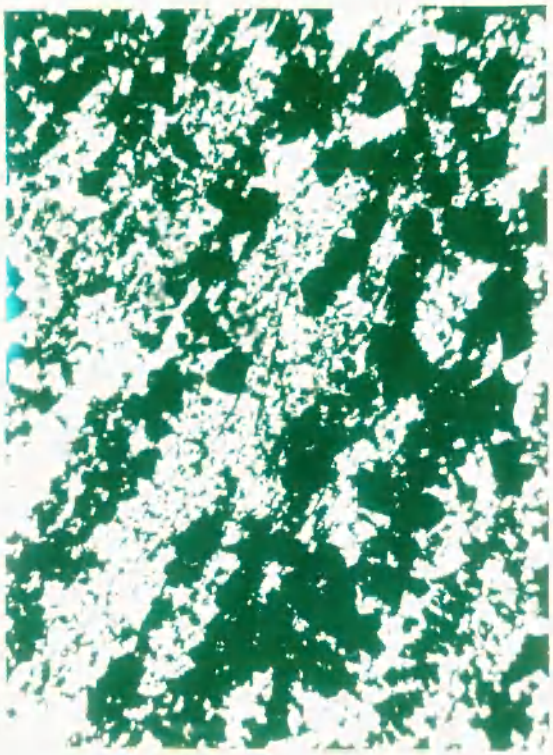

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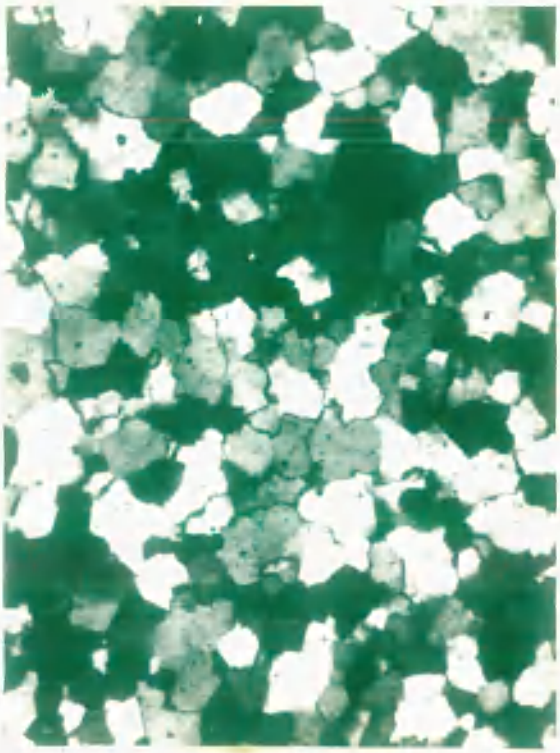

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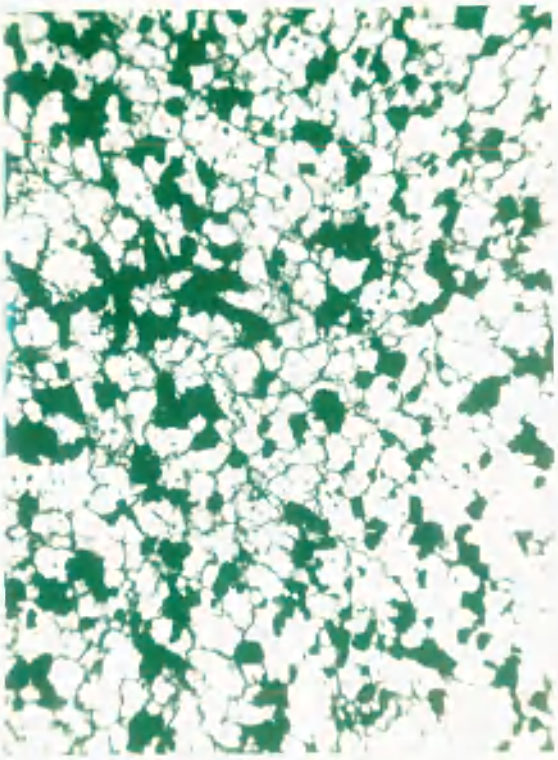

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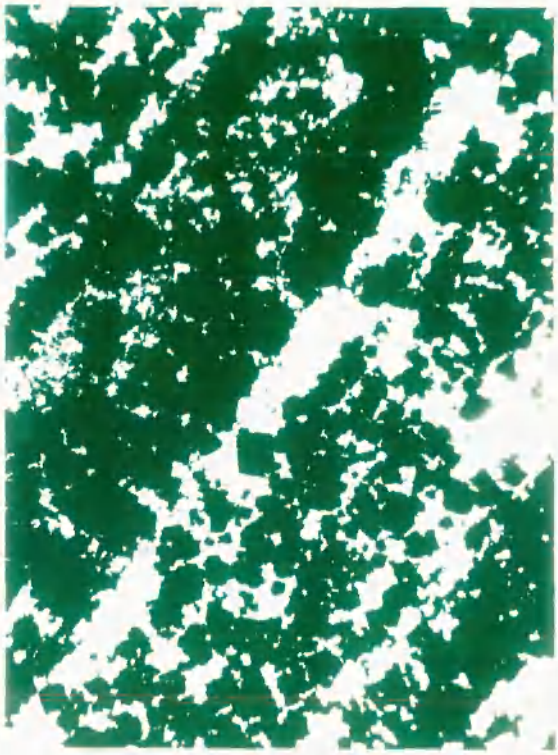

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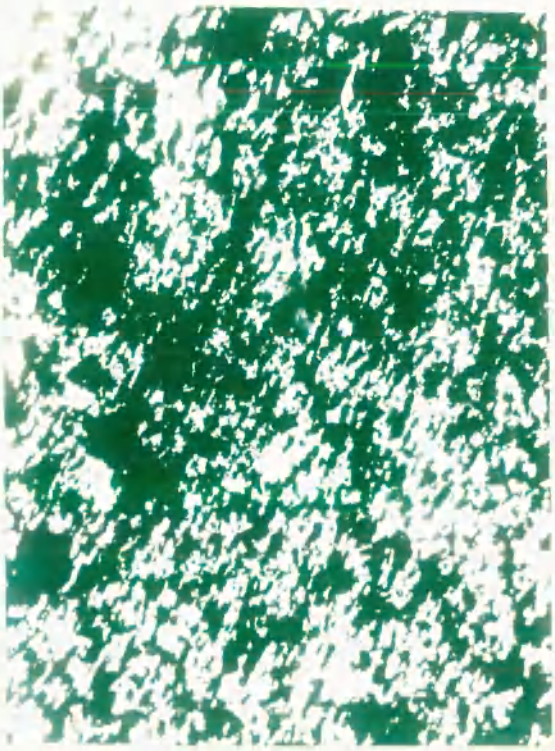

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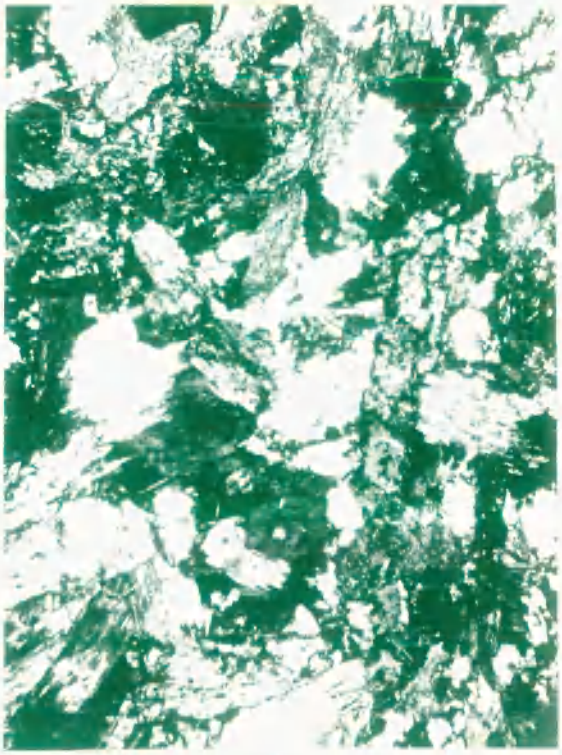

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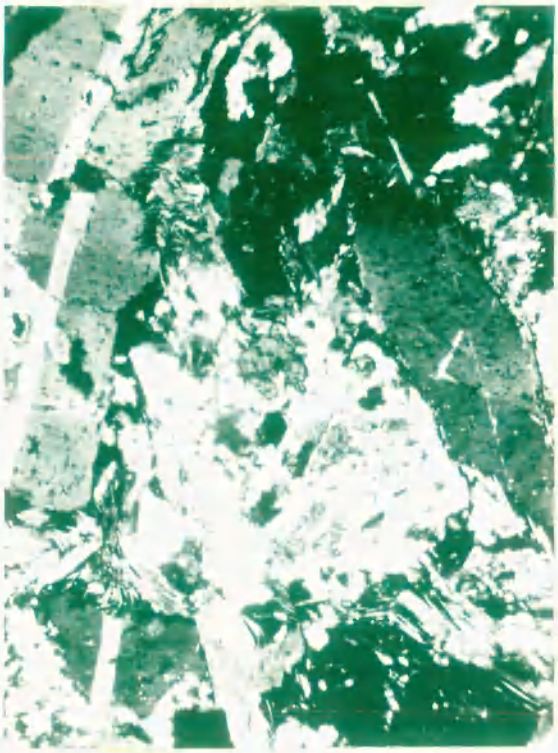

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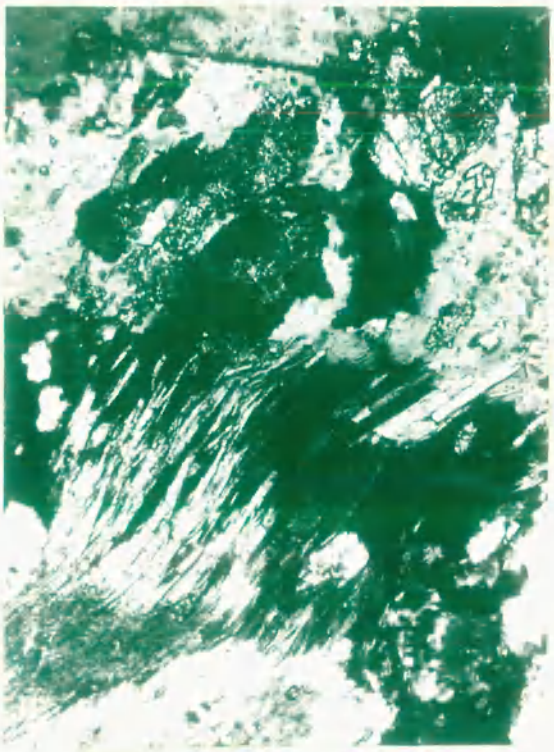

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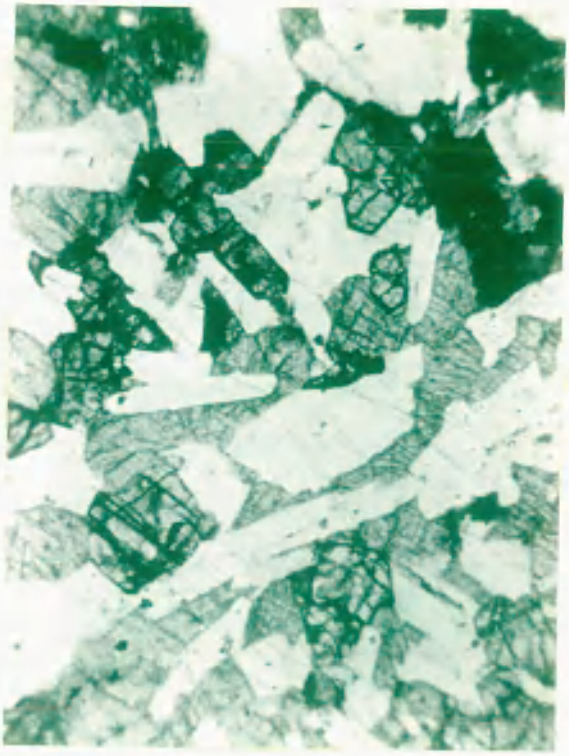

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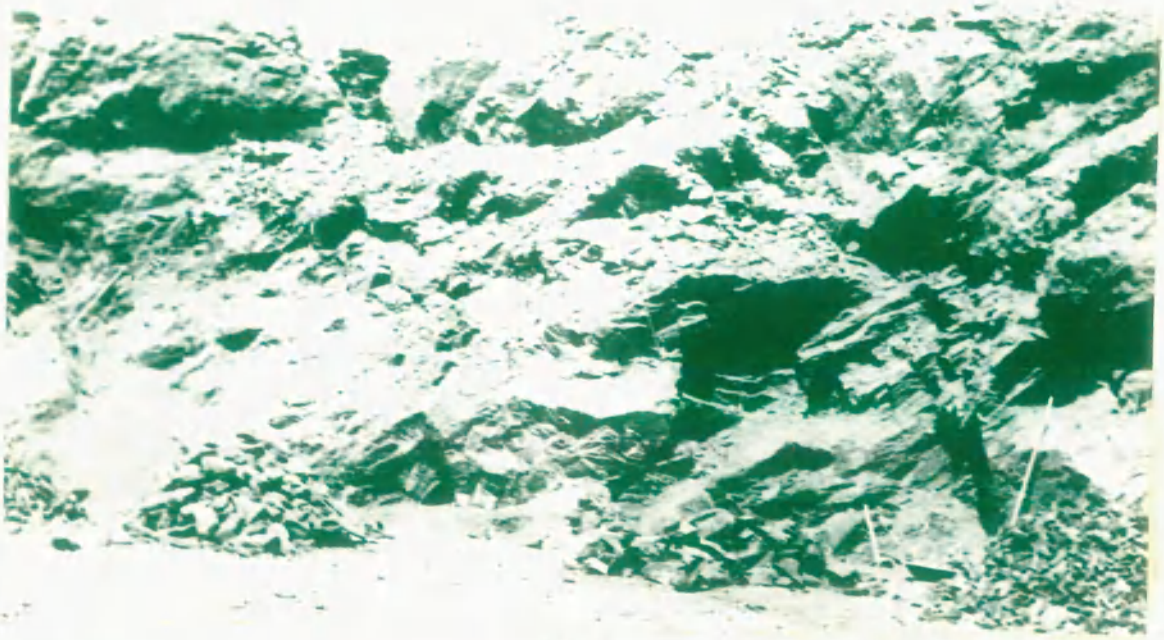

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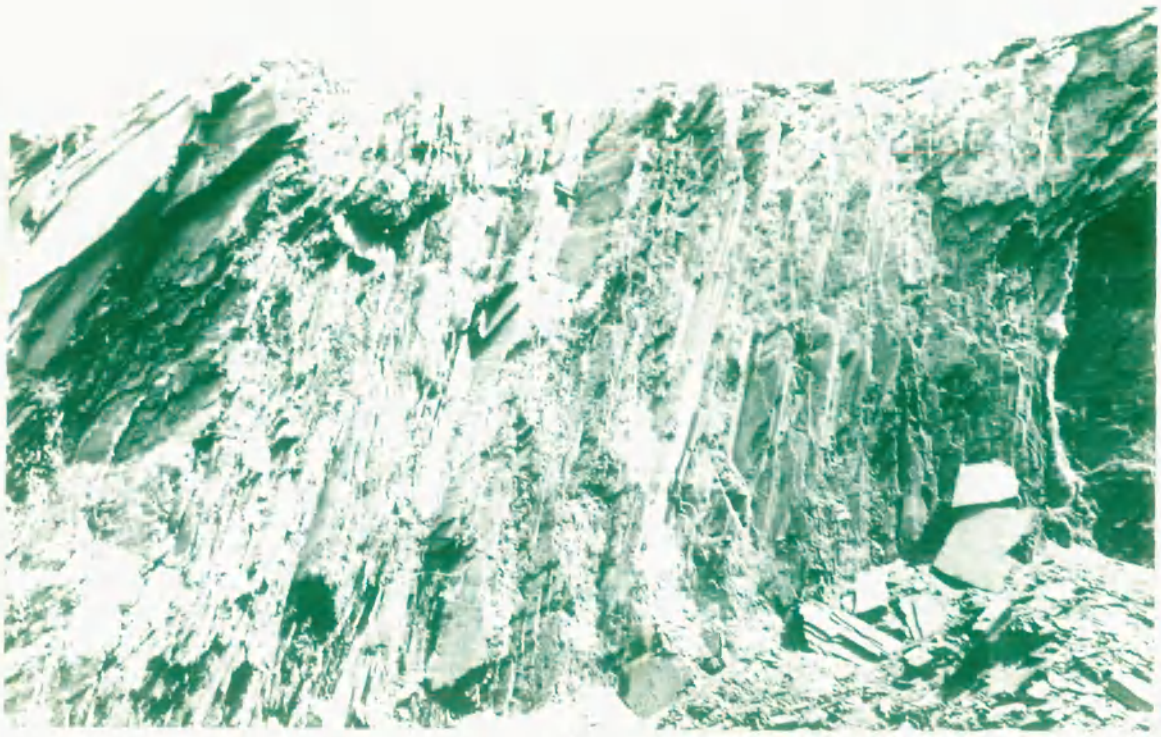

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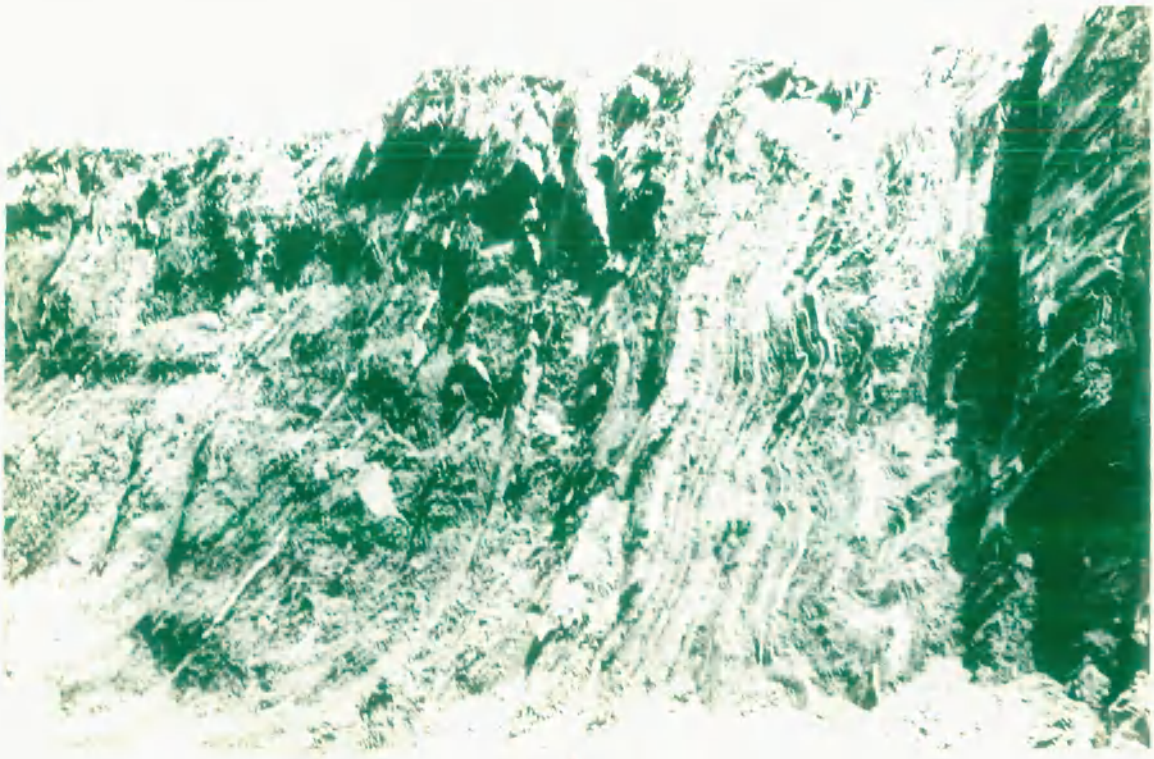

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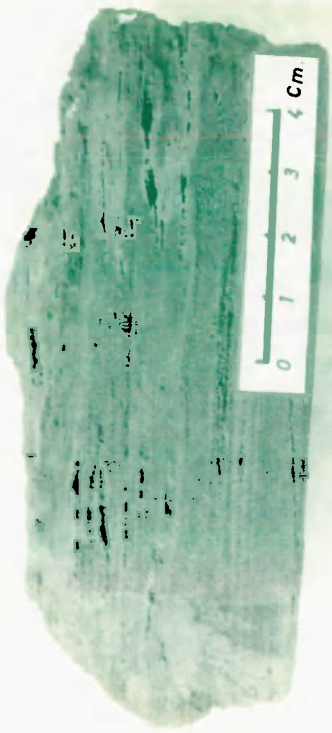

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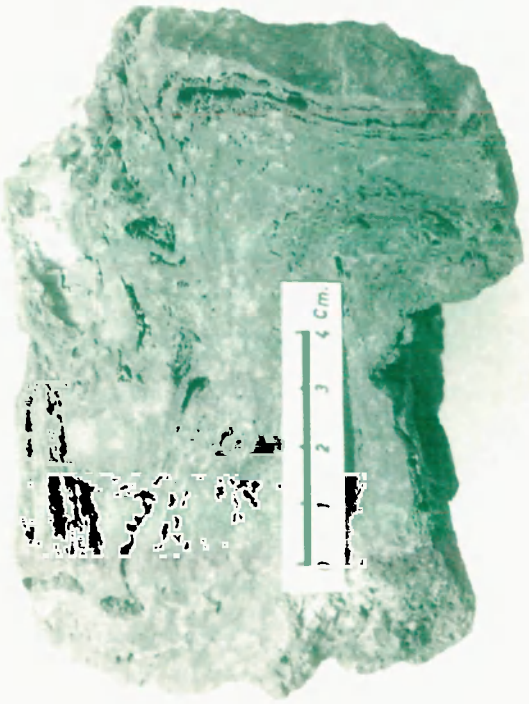

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PLATE. X

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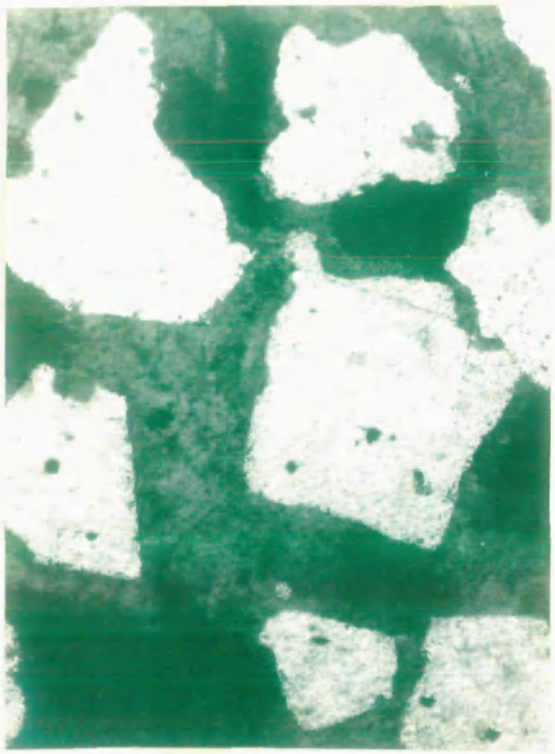

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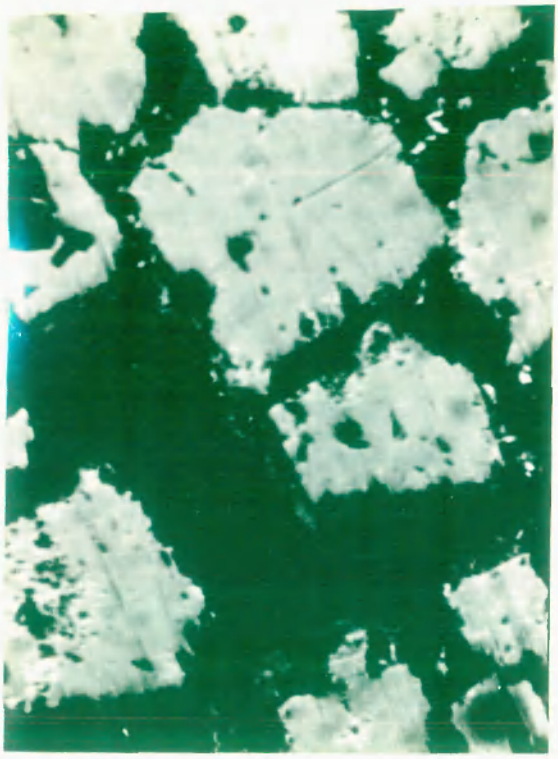
PLATE. XI



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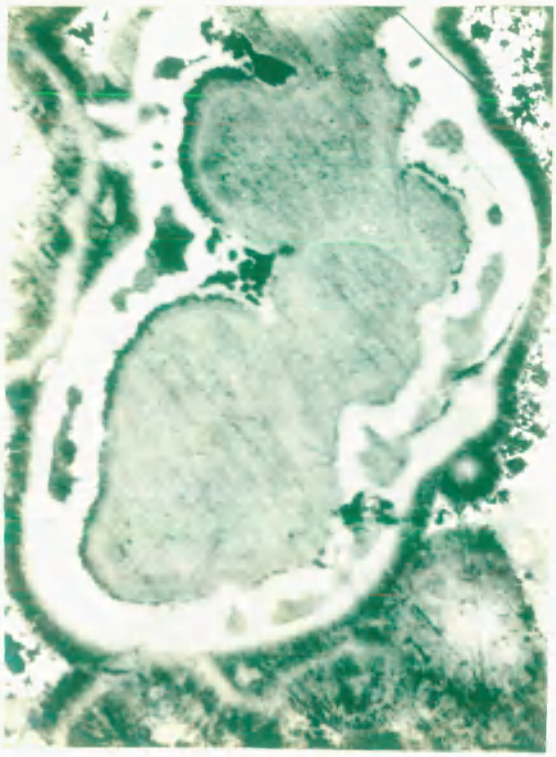

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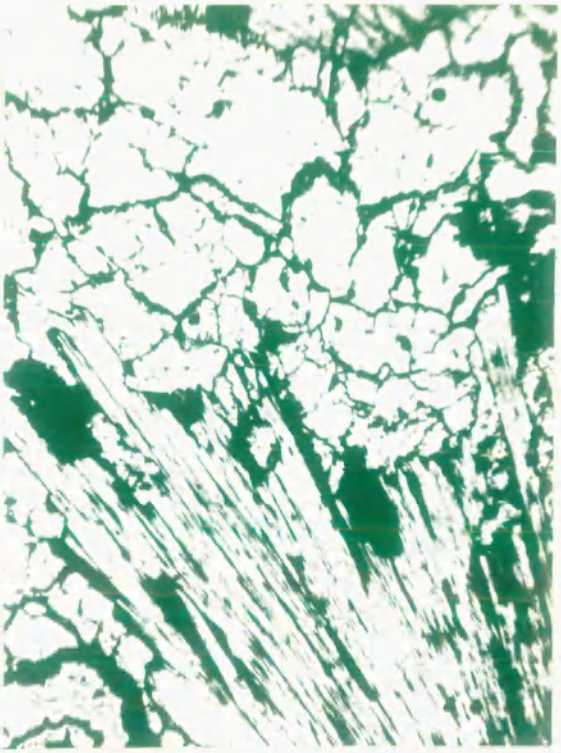

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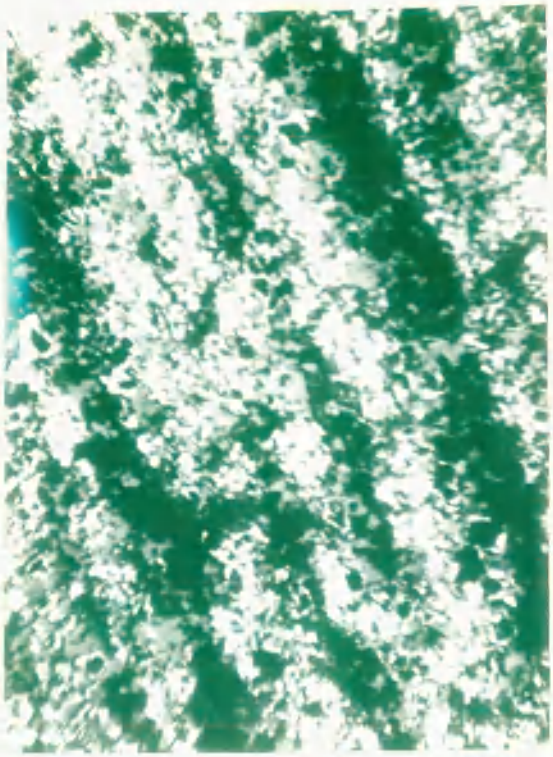
PLATE. XII



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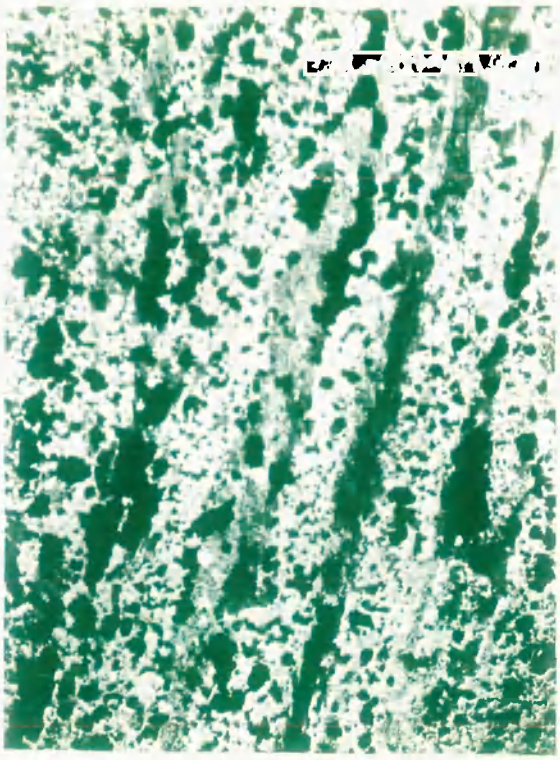

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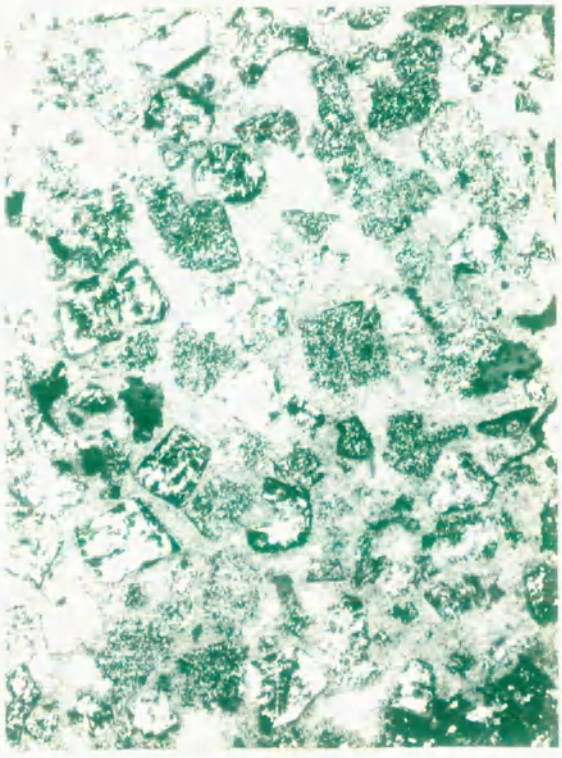

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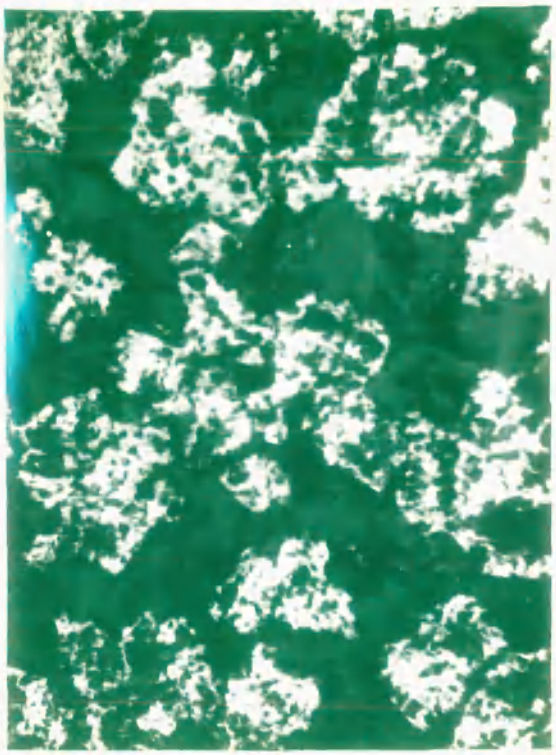

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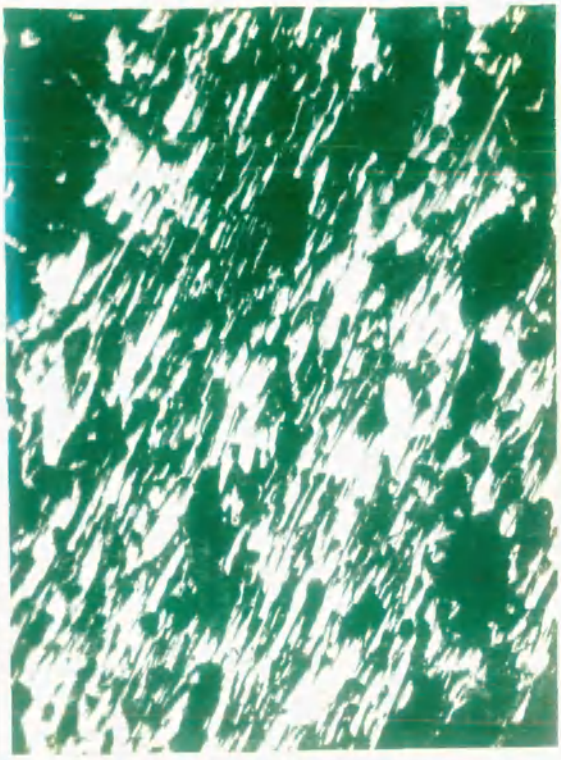

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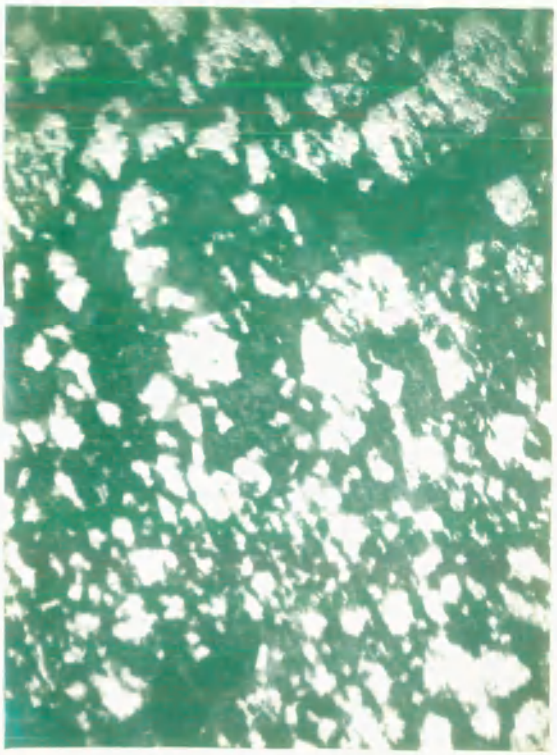

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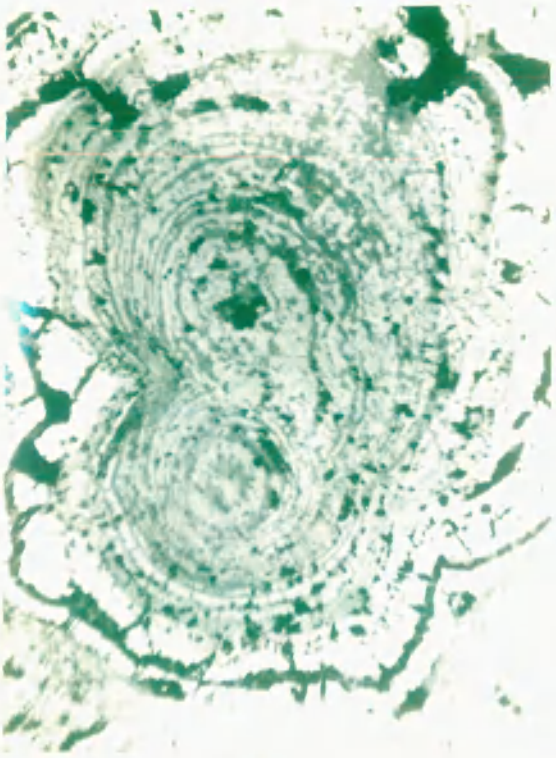
PLATE. XIV



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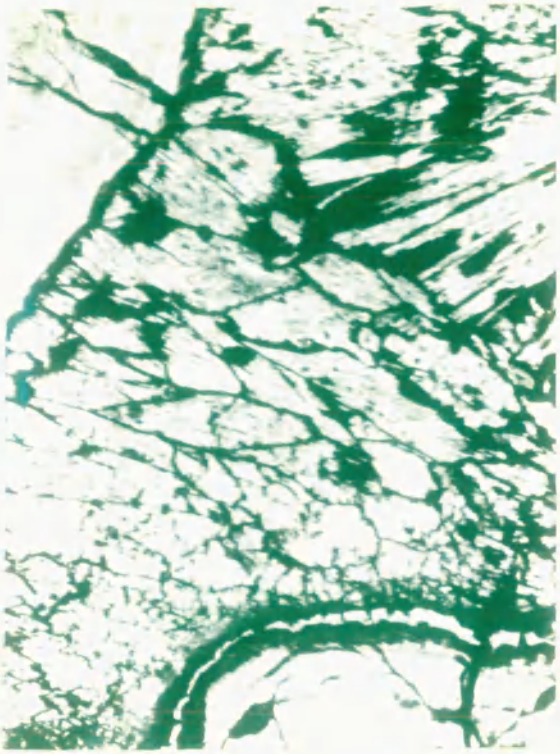

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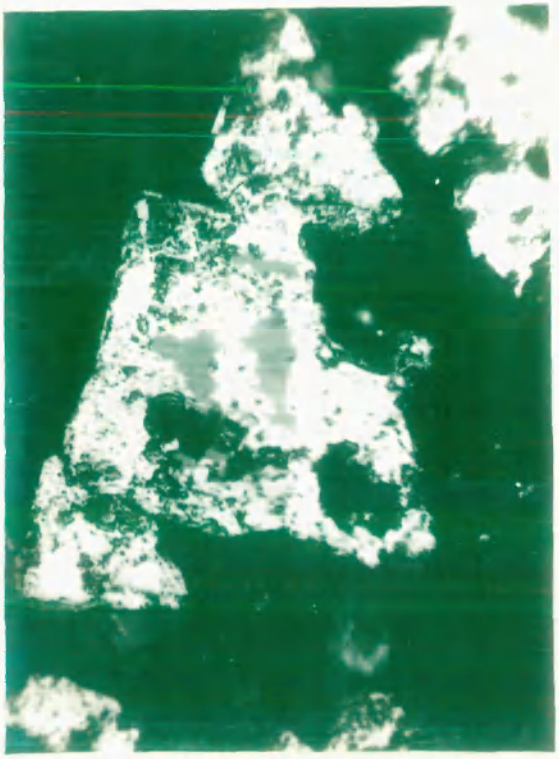

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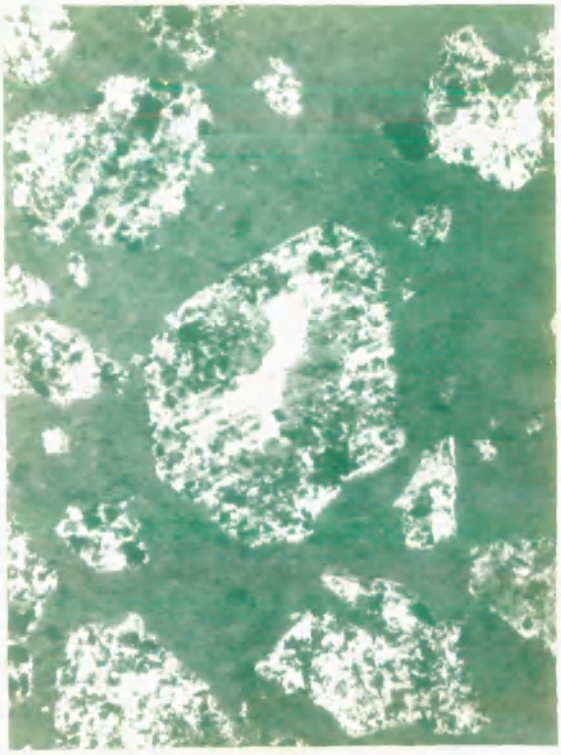

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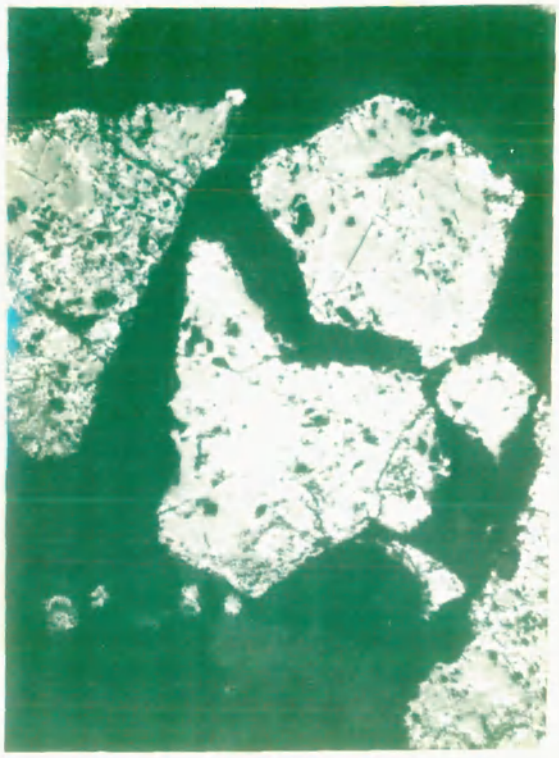

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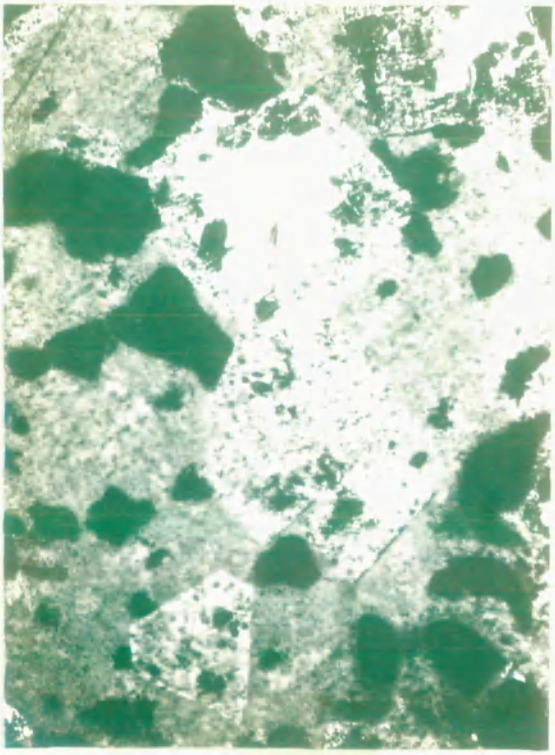

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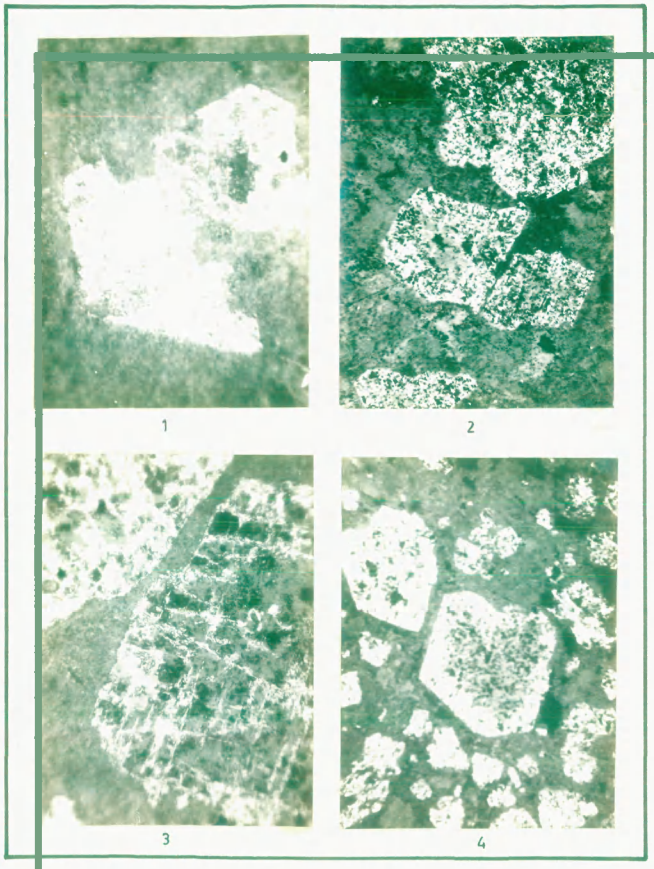
PLATE. XVI



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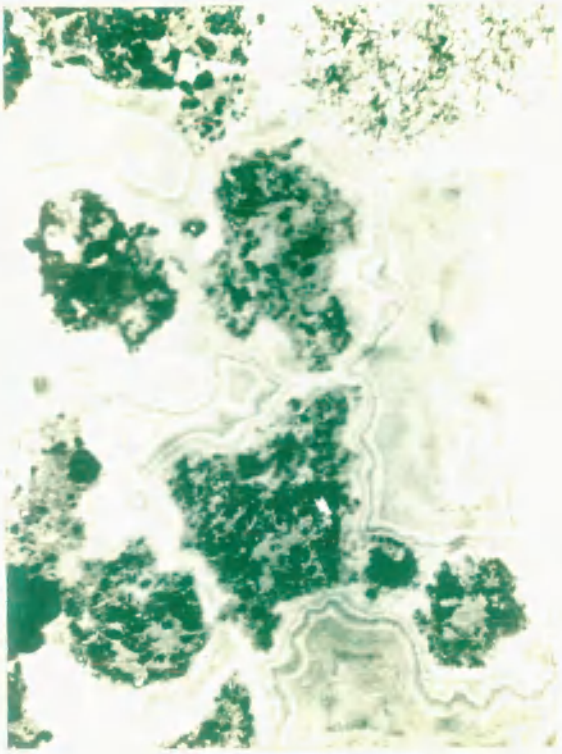

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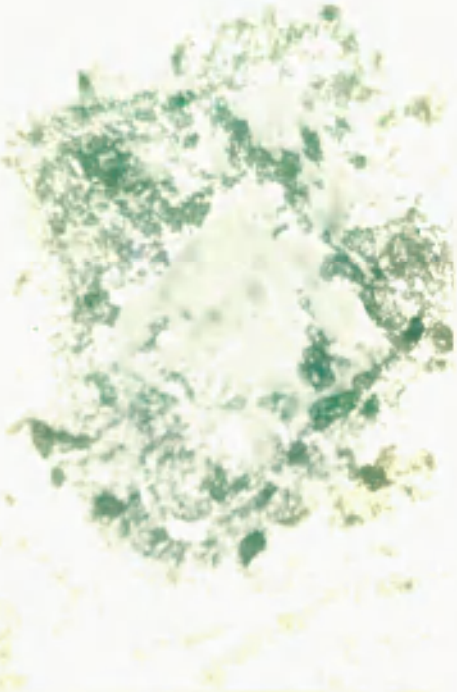

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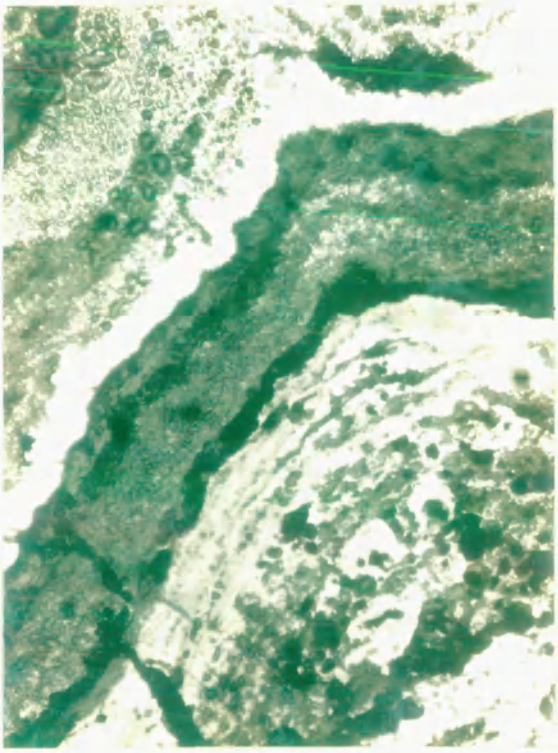

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